Implementing the Six Sigma Breakthrough Management Strategy to Reduce Bowed Pipe Defects in the Oil and Gas Industry, a Black Belt's Approach

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ABSTRACT

The effectiveness of The Six Sigma Breakthrough Management strategy was evaluated in the oil and gas industry, specifically at Vallourec Star. Statistical and process analysis were utilized to investigate the cause and effect relationship of input and output variables during the seamless rolling process. Implementation of the Six Sigma Breakthrough Management strategy has yielded significant results in various industries but there are not many examples of successful deployments in the oil and gas industry, more specifically in a seamless tube mill. Six Sigma was studied, adapted and deployed to meet the needs of the oil and gas industry and Vallourec Star. The adaptations included piloting on a high impact, high visibility opportunity within the seamless rolling mill. The chosen approach prioritized a hybrid bottom up and top down strategy rather than the traditional top down only approach adopted by more mature industries. Six Sigma has proven as an effective problem-solving methodology for the oil and gas industry and was successfully implemented. Vallourec Star was able to reduce pipe related defects by 70% while following the Six Sigma methodology.

ACKNOWLEDGEMENTS

Firstly, I would like to dedicate this thesis to my Mother, Kim Howell, to my beautiful wife Aulanna and to my son Chancellor. Thank you for believing in this dream and thank you for not giving up on me. Your love, your kind words and support were much needed throughout this process. I would also like to thank my Dad, Clarence Howell Jr., all of my siblings Tonnette, Nichole, Shawntera, Kris and Larry. I would like to thank my best friends, Dr. Okello, Lamar, Carrington, Gib and Thomas for holding me accountable and never accepting mediocrity. The village that raised this child is the reason I am where I am today and I thank you all for it.

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Chapter 1 INTRODUCTION

Recent growth in the oil and gas industry has raised the level of competitiveness for suppliers of seamless tubes and pipes. Vallourec Star is North America's leading supplier of seamless tubes and pipes, mainly dedicated to oil and gas applications. Vallourec Star is composed of three manufacturing sites: Youngstown, Ohio, Muskogee, Oklahoma and Houston, Texas. Vallourec Star's largest manufacturing site is located in Youngstown, Ohio. Vallourec Star's operations are dedicated to steel making, pipe rolling, heat treating, inspection and threading. The annual output capacity is approximately 500,000 metric tons of finished tubular products, of which 66% are dedicated to oil, country and tubular goods (OCTG). Other products include Line Pipe, Standard Pipe, Coupling Stock and Mechanical Tube. Vallourec Star is one of the many companies that belong to the Vallourec Group. Vallourec is the world leader in premium tubular solutions, mainly serving the energy markets [13]. Vallourec currently has 19,000 employees worldwide and a wide variety of operations ranging from, integrated manufacturing facilities and advanced Research and Development facilities.

This growth in the industry can be attributed to the natural gas and oil deposits found in the Marcellus and Utica shales located in the Appalachian Basin States of Pennsylvania, West Virginia, southern New York and eastern Ohio. In 2010 Vallourec broke ground on a state-of-the-art Fine Quality Mill (FQM) dedicated to supplying seamless tubes to this new and growing market. This new mill will help to supplement the product offering from the current Multi-stand Pipe Mill (MPM). Figure 1-1 highlights the capability of the new mill.

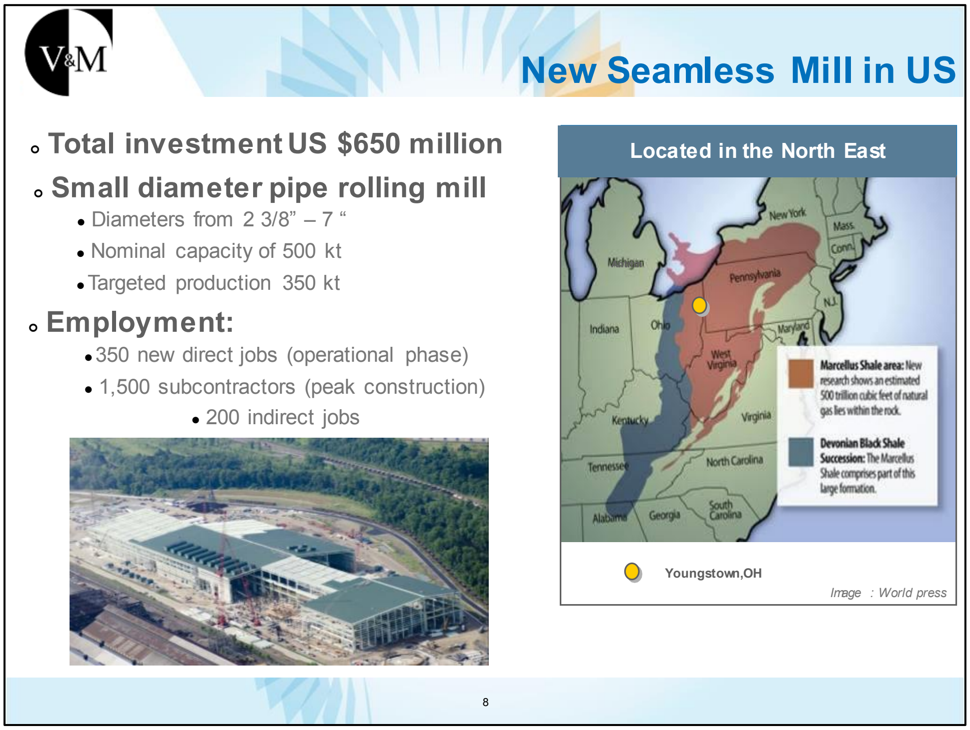

Figure 1-1: Highlights of the Fine Quality Mill located in Youngstown, OH

The oil and gas industry is a mature industry filled with a rich history, a strong blue collar workforce and an even stronger resistance to change. Illustrated in figure 1-2 this industry has experienced many peaks and valleys forcing it to continuously evolve and innovate. According to Macrotrends over the past 70 years the price of crude oil per barrel has fluctuated significantly, dropping as low as $25 (Feb 1961) and rising as high as $161.28 (June 2008). Over this 40-year time period there were several peaks and valleys influenced by several factors ranging from geo-political and economic events.

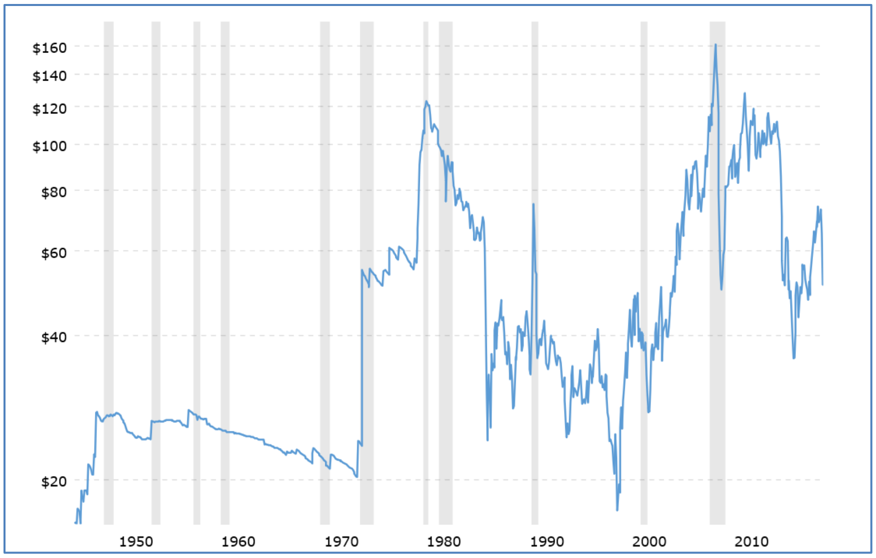

Figure 1-2: Price volatility of crude oil over the past 70 years

Historically breakthroughs in Research and Development have served as the main drivers in helping this industry to sustain during tough market situations. Even with these innovations there are still shortcomings for organizations to meet stakeholder expectations, customer needs and ensure their workforce stability. In 2016 Forbes published an article that highlighted 15 large oil and gas companies that had declared for bankruptcy [15]. The biggest bankruptcy debt belongs to Pacific Exploration & Production, who at the time was $5.3 billion in debt.

Change inside of this industry is evident so it is imperative for organizations to focus their resources on improving operations internally to weather the effects of a volatile industry. According to Price, Waterhouse, Cooper clients are looking to improve productivity and to drive costs down to deliver sustainable growth [16]. Improving an organizations internal quality can help to drive down costs significantly and to improve responsiveness to their customers. The cost of non-quality and the reduction of defects will serve as the primary driver to improve productivity and drive cost inside of Vallourec Star's seamless tube mill.

The Break Through Management Strategy or better known as Six Sigma has helped companies in many industries remain competitive and profitable in changing climates. With its focus aimed in a few key areas, it has helped propel companies from extinction to industry leaders. Companies ranging from General Electric, Honeywell, DuPont, Johnson Controls, Motorola, Caterpillar, Polaroid, Chevron, Dow Chemical, Samsung and many others have ridden the Six Sigma wave to significant improvement. In this research the Six Sigma methodology will be the primary tool used in helping to once again transform the oil and gas industry. The rigor and use of sophisticated problem-solving tools will serve as the primary drivers to deliver a significant impact inside of this industry. In this work Six Sigma will be the primary driver used to show improvements within Vallourec Star, more specifically in the seamless tube mill.

1.1 Seamless Tube Manufacturing

According to Vallourec & Mannesmann the seamless tube process is achieved by piercing a solid billet and rolling in a Mannesmann mill to form a central bore [4]. This process was patented in 1885 by brothers Max and Reinhard Mannesmann. Controlling critical parameters during the rolling process are keys to ensuring defect free products at the completion of the forming process. Although seamless tubes were recently invented in 1885, Archeological evidence suggests pipes have been around as early as 2000 B.C. According to Romanowski [12] the first use was by ancient agriculturalists who diverted water from streams and rivers into their fields. Fast forwarding to the 20th century modern day seamless tubes are used primarily in oil and gas applications, power generation, construction and automotive. The main competition of seamless tubes are electric resistance (ERW) welded tubes. ERW tubes are manufactured by cold forming a flat steel strip into a rounded tube and passing it through a series of forming rollers to obtain a longitudinal seam. The two edges are then simultaneously heated with a high frequency current and squeezed together to form a bond. The main benefit of seamless tubes is there is no weld seam where the steel is joined together. Not having a weld gives seamless pipe the ability to handle higher pressure applications [18]. Because of this, seamless tubes are the preferred product in complex applications and in regions that require more robust materials. Resulting in the need for high quality and defect free material.

The Mannesmann process built a bridge between past methods and the new century of manufacturing. The Mannesmann process improved quality and manufacturing efficiency. The Mannesmann piercing process is diagramed in figures 1-3 and 1-4. The piercing process is the first transformation step in the forming process for a seamless tube. After the billet is pierced the hollow shell is rolled in a mandrel mill. The primary purpose of the mandrel mill is to reduce the outside diameter and wall thickness. A tube that has passed through the mandrel mill is referred to as a mother tube. The mother tube is further reduced and finished by a stretch reducing mill, which will finalize the forming process [4].

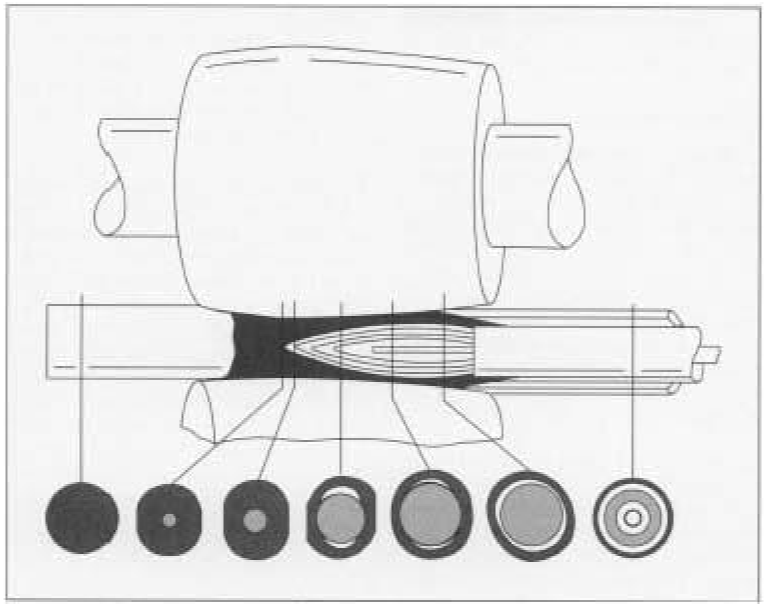

Figure 1-3: Mannesmann Piercing process: Hollow shell inside of piercer mill

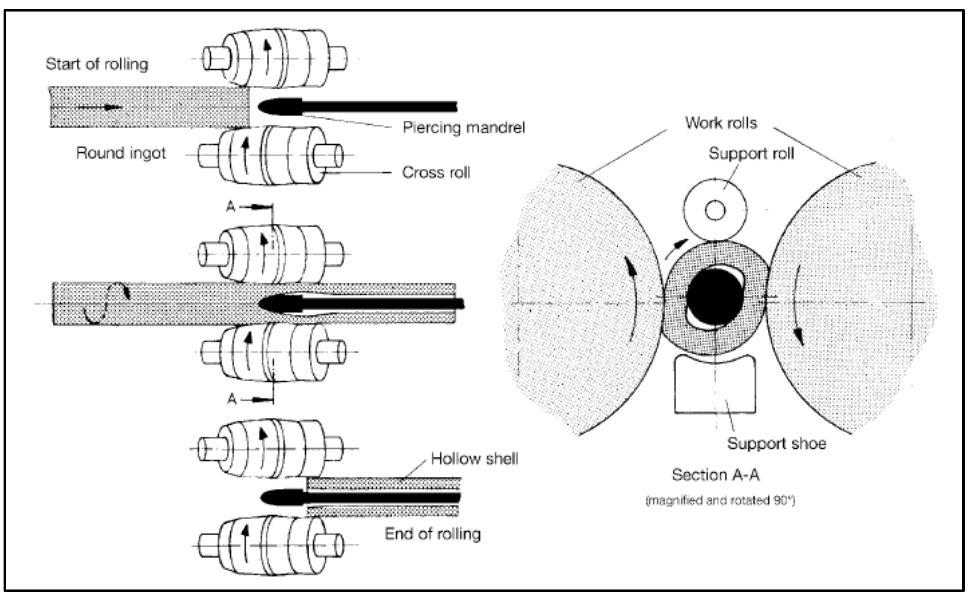

Figure 1-4: Mannesmann Piercing process: Hollow shell inside of piercer mill

Vallourec and Mannesmann believe there are four main processes associated with manufacturing seamless tubes. Heating, piercing, elongation and final rolling. Figure 1-5 illustrates the various methods for each. According to Vallourec there are three main methods for billet reheating, two methods to pierce billets, nine methods to elongate tubes and one method for final rolling. For heating billets three furnace variations are utilized by Vallourec. A soaking pit furnace, a rotary hearth furnace and a walking beam furnace. For piercing billets Vallourec utilizes the push press and cross roll piercing methods. For elongation, the methods include drawing, cross rolling, forge rolling, the push bench, the asset mill, the plug mill, mandrel mill, the pilger mill and the reeler mill. For final rolling, sizing and stretch reducing mills are the main techniques.

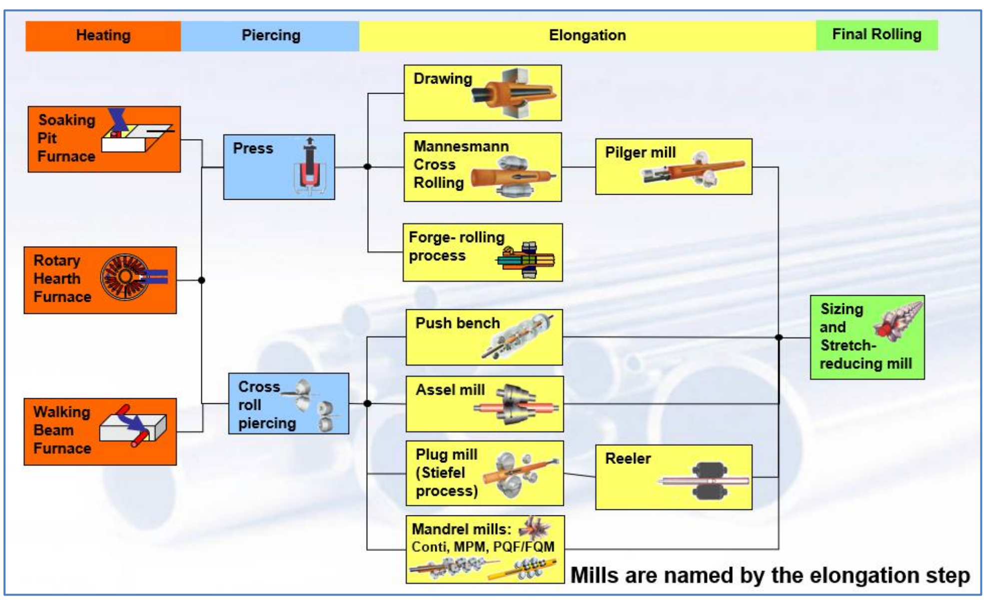

Figure 1-5: Main forming steps for seamless tube manufacturing

1.2 Seamless Tube Defects

In the oil and gas industry the cost of non-quality is utilized to measure how well an organization manages defects. Defects are classified as physical, visual, clerical or transactional. Defects specific to seamless tube manufacturing primarily affect the pipe outside diameter (O.D.) or the inside diameter (I.D). Tube defects can be physical, visual or mechanical. Some defects are visible to the eye, some need special equipment to detect and others affect the microstructure of the material. Table 1-1 gives an overview of the common defects found within the seamless tube process. Common seamless mill defects can be classified into 9 categories. Pitting, slivers, gouge, hook or bend, bow, tailing, wall variation, dimensional and mechanical [18]. There are many defects that exist within each category but the classification can vary significantly depending on the forming process and manufacturer.

Area	Defect Type	Description
ID	Pitting	localized corrosion resulting in small holes
ID	Slivers	localized damaged caused by addition of material
ID/OD	Gouge	localized damaged caused by the removing of material
OD	Hook or bend	Distortion to the end of the tube located in the thread area
OD	Bow	Distortion to the body of the tube that inhibits rolling
ID	Tailing	localized damage caused by addition of materila
ID	Wall variation	Difference in internal diameter in different quadrants of a tube
ID/OD	Dimensional	Out of tolerance range
ID/OD	Mechanical	Does not meet physical properties

Table 1-1: Seamless tube defect categories

1.3 History of Six Sigma

Mikal Harry was one of the original architects of Six Sigma while working at Motorola in the 1980's [5]. According to Harry and Schroeder Six Sigma was born out of a need for Motorola to improve its quality. In 1979 Top Executive Art Sundry proclaimed that poor quality was the real problem within the multi-billion-dollar enterprise and challenged Motorola's employees to make a change. That change came in the form of Six Sigma. In its infancy the strategy focused on a simple, consistent way to track and compare performance to customer requirements (the Sigma measure) and an ambitious target of perfect quality (the Six Sigma goal: 3.4 defects out of a million opportunities.). For Motorola Six Sigma introduced a common language for performance measurement. No matter if you worked on the shop floor or in the finance department Six Sigma gave employees a common language on how performance was evaluated [5]. Illustrated in Table 1-2.

DPMO	Sigma Short Term	Yield	Cpk	% Defective
3.4	6	99.99966	2	0.000340%
233	5	99.98	1.67	0.023300%
6,210	4	99.4	1.33	0.621000%
66,807	3	93.3	1	6.680700%
308,538	2	69.1	0.67	30.853800%
691,462	1	30.9	0.33	69.146200%

Table 1-2: The sigma measurement system

Figure 1-6 Illustrates the large gap between being good and achieving six sigma. This figure gives a very clear example of how to use the sigma scale to measure performance in any business environment. A three-sigma process results in 20,000 lost mail articles per hour out of a million but a process operating at a six-sigma level loses only 7 per hour.

Table I. Importance of Six Sigma—99% is not good enough	
99% good: 3 sigma	99.99966% good: 6 sigma
20 000 lost articles of mail per hour	7 mail articles lost per hour
Unsafe drinking water for 15 min each day	1 unsafe minute of water supply every 7 months
5000 incorrect surgical operations per week	1.7 incorrect operations per week
2 short or long landings at most major airports each day	1 short or long landing every 5 years
200 000 wrong drug prescriptions each year	68 wrong prescriptions per year
No electricity for 7 h each month	1 h without electricity every 34 years

Figure 1-6: Three sigma performance vs Six sigma performance

Six Sigma is the business process that allows companies to drastically improve their bottom line by designing and monitoring everyday business activities in ways that minimize waste and resources while increasing customer satisfaction. Six Sigma guides companies into making fewer mistakes in everything they do [5]. By taking a two-fold approach, Six Sigma picks up where other quality initiatives fall short. The first area focuses on improving quality and the second on deploying its method.

Six Sigma integrates the improvement tools that have proven effective over the years into a comprehensive approach that improves both customer satisfaction and the bottom line. As a result, Six Sigma builds on what has been successful in the past and takes performance improvement to the next level of effectiveness [5]. Some real-world examples include, Motorola, Allied Signal and General Electric. In a ten-year span Motorola saw five-fold growth in sales with nearly 20 percent growth in profits. Allied Signal, later known as Honeywell saw savings of $600 million dollars per year from 1990 – 1999 due to the implementation of Six Sigma. General Electric experienced a payback of $750 million dollars in 1998 and $1.5 billion in 1999.

Allied Signal and General Electric further popularized and proved the Six Sigma method could work in various industries in the 1990's. Their success influenced and encouraged other companies to take on Six Sigma initiatives. Companies such as Dupont, Dow Chemical, 3M, Ford, and American Express have adopted and integrated The Breakthrough Management Strategy into their business strategies. Each company using the method in a different way to drive significant improvement to the bottom line.

1.4 Six Sigma Quality and Six Sigma Methods DMAIC

Six Sigma is divided into two distinct categories, Six Sigma Quality and Six Sigma Methods. Six Sigma Quality focuses on achieving a goal of 3.4 defects per 1 million opportunities while Six Sigma Methods focuses on implementing a fact-finding problem-solving method driven by DMAIC (Define, Measure, Analyze, Improve, Control). Six Sigma is modeled after a normal distribution or better known as a bell curve. The normal distribution is a continuous distribution that is symmetrical around both sides of the average. As shown in figure 1-7.

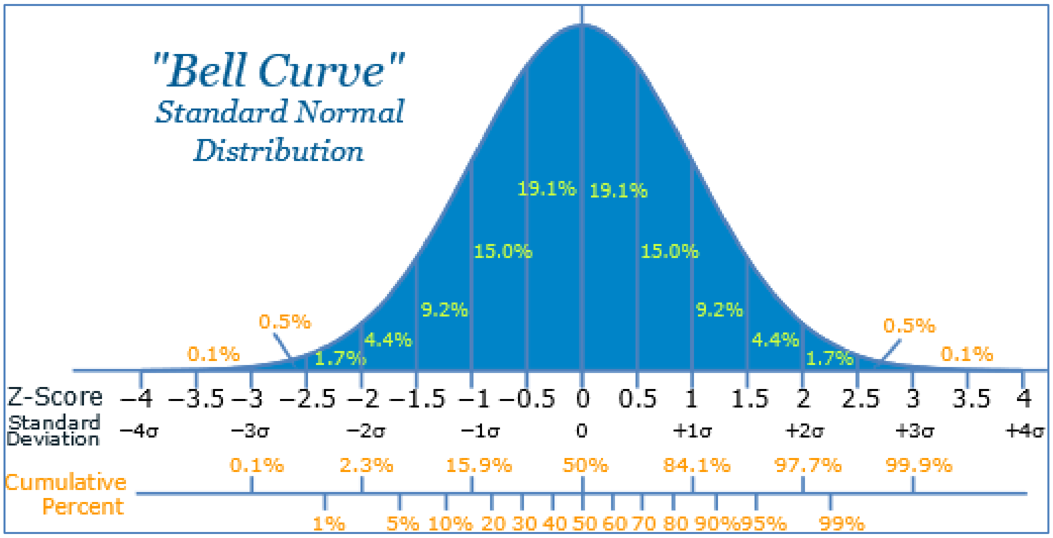

Figure 1-7: Normal Distribution

DMAIC is used to deliver the most useful process variables (X's), also known as Red X's to the Improve (I) phase. Measure (M) and Analyze (A) collect X's and then filter out the less important ones [11].

1.5 Six Sigma Data Analysis Approach

The purpose of data analysis is the turn numbers into meaning [10]. Statistical data analysis involves collecting and exploring data from a given population. Data analysis is a necessary step in finding the root cause of any specific problem. Six Sigma relies on statistical logic in order to validate decision making. Six Sigma categorizes its tools into two main categories:

- **Data Analysis**: Data analysis is used to find patterns, trends, and other difference that can suggest, support, or reject theories, about the cause of defects.

- **Process Analysis**: A detailed look at the existing key process that supply customer requirements in order to identify cycle time, rework, downtime, and other steps that don't add value for the customer [10].

The tools Six Sigma employs for data analysis are categorized into two groups, simple and advanced:

- **Simple**: Pareto charts, run charts, control charts, histograms, cause and effect analysis, relationship diagrams, scatter plots,
- **Advanced**: Hypothesis testing, Analysis of variance (ANOVA), Multivariate analysis, regression and correlation analysis and Design of Experiments (DOE).

The type of data available is used to determine which approach is best. Six Sigma groups data in two categories: Variables data and attribute data.

- **Variable data:** Comes from measuring and has a continuum of possibilities. Statistical distributions associated with variable data are not limited to, but include the Normal Distribution, T Distribution and the Weibull Distribution.
- **Attribute data:** Comes from counting and cannot generate continuum. Attribute data is discrete and employs statistical distributions such as Poisson, Binomial and Hypergeometric. Go/No-Go inspection data is discrete [11].

1.6 Regression and Correlation Analysis to Understand Relationships

One of the advanced statistical tools of Six Sigma is regression and correlation analysis. According to Pande, regression analysis can help determine the degree of correlation between cause and effect. This analysis tool is useful in testing the root cause of a problem, in understanding the influence of a single factor or multiple factors on a result and predicting the performance of a process, product or service. Regression analysis is made up of three methods. First, the correlation coefficient (r) which is used to determine whether and how strongly factors are correlated. The "r" correlation coefficients range from -1 (a perfect negative correlation) to +1 (a perfect positive correlation). The closer the coefficient falls to +1 or -1, the stronger the correlation is between the selected factors. Second, the correlation percentage (r^2), which is an indicator of the strength between the cause and response variables. Values range from 0% - 100%. A larger the percentage gives indication to how much variation is explained in the model. The third and final method is regression. There are several forms of regression (linear, multiple, step-wise, binomial, etc..) but they all concentrate to use existing data to predict the future. The type of data dictates which tool will yield the most accurate results.

1.7 Problem Statement

This research will explore the effect of implementing the Six Sigma methodology to minimize bowed pipe rejects inside of Vallourec Star. This research will focus to identify cause and affect relationships between input and output variables in the seamless rolling process. Including billet reheating, piercing, rolling, elongation, and cooling. Ultimately this research will aim to significantly reduce the defects caused by bowed pipe rejects that occur during the seamless rolling process. The documented history and proven results inside of several former or current industry leading organizations sets Six Sigma above others. Six Sigma's disciplined focus on problem solving and process change through rigorous data collection and statistical analysis fit the business need inside of Vallourec Star's Pipe Mill.

This research will utilize the tools of Six Sigma to identify and control the critical process variables that influence bowed pipe rejects within Vallourec Star's Seamless Tube Mill. The expected results include a 70% reduction in yield loss due to bowed pipe scrap, a 33% reduction in mill delay time due to bowed pipe handling and a 10% improvement in mill capacity. The forecasted results were the output of several preliminary working sessions with team members inside of Vallourec Star's Pipe Mill. These results will be achieved by following the Six Sigma DMAIC process and utilizing data collection, statistical data analysis and hypothesis testing.

1.8 Purpose of Research

Vallourec Star is losing over $2 million dollars per year in lost opportunity costs due to bowed pipe rejects inside of its MPM mill. In response, this research will answer the question of what causes certain products to bow enough to cause rejects. This research will do so by identifying critical process parameters during the seamless rolling process. The current operation within the seamless mill at Vallourec Star currently average scrap levels of around 90 metric tons per rolling cycle. This level of scrap equates to a loss of $300,000 annually due to lost material. Reject material must be physically removed from the mill by overhead crane causing the entire mill to shut down. These shutdowns cause significant downtime thus preventing Vallourec Star to meet the demand of their customers. A cross functional team will serve as the primary driver to gather data, test hypotheses and run experiments. The team will build on previous knowledge and experiences, and use the Six Sigma Methodology as a roadmap. The output of this research would be a significant improvement in Vallourec Star's bottom line. The output of this research will be self-sustaining and serve as the foundation to identify other improvement efforts that follow the Six Sigma methodology. This implementation will focus on developing the process opposed to only focusing on achieving results.

There are five core competencies this research will focus on during implementation:

Step 1: Identify Key Performance Indicators (KPI's) and key customers

Step 2: Define customer requirements

Step 3: Measure Current Performance

Step 4: Prioritize, Analyze, and Implement Improvements

Step 5: Expand and integrate the Six Sigma System

In summary, this research will focus to advance the integration of the Six Sigma methodology in the oil and gas industry and create a roadmap in order to achieve results during the seamless rolling process. It is important the project roadmap is clear, flexible and most importantly impactful. Existing implementations across various industries will be a key factor in supporting this culture change in the oil and gas industry.

1.9 Method of Research

The methodologies in the work presented will provide evidence of implementation of the Six Sigma within Vallourec Star's operations. The approach will include:

- Current state analysis of Vallourec Star's seamless rolling process
- Development of Key Performance Indicators (KPI's) in the seamless rolling process
- Development of a process that will include the use of statistical analysis through hypothesis testing, regression analysis and ANOVA (Analysis of Variance).
- Creation and deployment of a roadmap for improvement

1.10 Expected Results

The results of this research shall demonstrate the flexibility of the Six Sigma methodology. It is expected that the implementation of this method will bring significant improvement within Vallourec Star, including:

- A 70% reduction in yield loss due to bowed pipe scrap
- A 33% reduction in delay time related to the handling of bowed pipe scrap
- A 10% improvement in mill capacity

- A self-sustaining process that generates, completes and audits Six Sigma projects
- Improved employee engagement in Continuous Improvement projects
- Defined set of metrics for measuring the success of the continuous improvement process

Chapter 2 BACKGROUND & LITERATURE REVIEW

2.1 Introduction

Six Sigma is a forward-thinking initiative that is designed to change the way corporations do business. Six Sigma offers specific methods that help companies re-engineer and or re-create processes in a way that defects and errors never arise [5]. Taking quality control to the next level, Six Sigma utilizes rigorous data gathering and statistical analysis to pinpoint sources of error and ways to eliminate defects at the source. Six Sigma and the Breakthrough Strategy are two distinct elements. Six Sigma is the philosophy and the goal, 3.4 defects per million opportunities. The Breakthrough Strategy provides the means to achieve that goal through a highly focused system of problem solving. Six Sigma is the Land of Oz; the Breakthrough Strategy is the Yellow Brick Road that takes you there [5]. Methods from the Six Sigma Breakthrough Strategy can be applied in the Oil and Gas Industry. This will showcase the ability of the methodology to generate significant improvements across any industry no matter the level of familiarity. The impact of Non-Quality costs (NQC) due to bowed pipe defects inside of Vallourec Star's MPM mill creates a sizeable need for a long-term solution to be explored. According to the Society of Petroleum Engineers [20] historically in the Oil and Gas industry, improvements were led by advancement in downstream operations at rig sites not from far upstream operations inside of mills. This literature review aims to highlight how other companies utilized Six Sigma and how they can help to significantly reduce bowed pipe defects at the MPM mill.

2.2 Pioneers of Six Sigma: Allied Signal / Honeywell

According to Harry and Shroeder [5] Allied Signal was the first corporation to implement Six Sigma as we know it today. Larry Bossidy, a former General Electric executive brought Six Sigma over to Allied Signal in the early 1990's, later known as Honeywell following a merger in 1999. In 1991 Lawrence A. Bossidy left GE to take over an ailing AlliedSignal as CEO. In his new role Bossidy immediately set things in motion with reducing corporate waste, better motivating employees and setting formidable financial targets. Under his leadership AlliedSignal went from having a market value of $4 billion dollars in 1991 to a market value of $29 billion by the end of 1998. This shift in performance is largely a result of Six Sigma Initiatives.

The research of Harry [5] highlights, Bossidy utilized Six Sigma to improve process and product quality. The implementation included widespread employee training and how to adapt these principles into their different business units. Six Sigma was a new way of life for AlliedSignal. During the summer of 1997, for example, a mysterious shutdown of the Boeing 777 air supply control system manufactured by AlliedSignal occurred 4 times within 6 weeks. Each time on a different airline in each case, loss of cabin pressure forced to pilot to perform an emergency descent. With AlliedSignal's reputation on the line, a cross functional team of more than 85 employees, customers and suppliers, led by Aerospace Equipment Systems, used the Six Sigma methodology to diagnose the problem and develop an innovative, cost effective software solution in 90 days. Not only did AlliedSignal please Boeing, it's customer, but it also helped Boeing's customers avoid tens of millions in potential lost revenue. Moreover, AlliedSignal avoided spending hundreds of thousands of dollars in development and retrofit costs.

As mentioned above Allied Signal eventually was re-branded as Honeywell. The implementation of Six Sigma for Honeywell included product reworks and the reduction in the design to certification process for aircraft engines. The aircraft division was able to reduce this lead time from 42 – 33 months through the application of these Six Sigma principles to the design process. In 1998 the company realized a 6 percent increase in productivity as well as record profit margins of 13 percent. Overall, Six Sigma has saved AlliedSignal/Honeywell $1.5 billion dollars from 1991 – 1998.

2.2.1 Pioneers of Six Sigma: Motorola

The Six Sigma Breakthrough Strategy has helped catapult numerous companies ahead of its competition in record timing since the early 1990’s. According to Pande, Neuman and Cavanagh [8] Motorola’s existence and successes are tied directly to Six Sigma. Six Sigma was founded, developed and revolutionized in the 1980’s at Motorola by Mikal Harry, Ph.D. What Six Sigma offered Motorola at that time was a simple, consistent way to track and compare performance to customer requirements (the Sigma measure) and a target, a target that is indicative of perfect quality (the Six Sigma goal). No matter product complexity or similarity, a sigma level could tell a universal story. With a high sigma level representing a lower number of defects present per unit of that particular product or service while a lower sigma level represents a higher level of defects are present. This process started Motorola on its quest for perfection, led with strong support from its chairman Bob Galvin. Six Sigma gained the much-needed traction to help Motorola not only stay competitive but to once again become an industry leader during the late 1980's throughout the 1990's.

Six Sigma focused its efforts around six concepts [9]:

1. General focus on the customer – Understanding the customers' processes and requirements
2. Data and fact-driven management – Managing your business with data
3. Internal process focus, management, and improvement – Focusing on internal processes in order to meet their customer requirements.
4. Proactive management – Acting ahead of events. Making and setting ambitious goals, establishing clear priorities; challenging current process instead of blindly defending old ways.
5. Boundaryless collaboration – removing the barriers that disrupt the flow of ideas and action up and down and across the organization.
6. Drive for perfection, tolerate failure – balance risks and being okay with occasional setbacks.

In the 1990's Motorola transformed its identity, from a company with a reputation of producing bad quality products into becoming an industry leader and Malcolm Baldridge National Quality Award winner. All behind its innovative improvement concept called "Six Sigma". During the first ten years Six Sigma helped Motorola achieve:

1. Five – fold growth in sales, with profits climbing nearly 20% per year

2. Cumulative savings based on Six Sigma efforts of $14 Billion
3. Motorola stock price gains compounded to an annual rate of 21.3%

2.2.2 Pioneers of Six Sigma: General Electric

In 1996 General Electric (GE) realized the gap between a three-sigma organization and a four-sigma organization was costing an astounding $7 to $10 billion dollars each year in scrap, reworking of parts, correction of transactional errors, inefficiencies and lost productivity. [5] At a 1996 all employees speech then CEO Jack Welch shared a new strategy called "GE 2000". According to Welch "GE Quality 2000 will be the biggest, the most personally rewarding, and, in the end, the most profitable undertaking in our history. We have set for ourselves the goal of becoming, by the year 2000, a Six Sigma quality company, which means a company that produces virtually defect-free products, services and transactions." Commitment from the top of the organization is a vital step in the deployment of this methodology. Consistency and clarity in objectives are also key in a successful deployment, GE did all this and more. Welch's 1996 announcement, planning to lead GE to Six Sigma by the year 2000 created a lasting impression on other companies looking for new ways to prosper in a world in which value-oriented consumers demanded quality goods and services. Welch outlined to his audience that "We will be required to reduce defect rates 10,000-fold, about 84 percent per year for five consecutive years-an enormous task, one that stretches even the concept of stretch behavior". During the calendar year of 1996 GE committed to training tens of thousands of employees in the Six Sigma problem solving methodology.

GE's Leadership Development Institute was committed to training 200 Master Black Belts, 800 Black Belts and 20,000 engineers in Design for Six Sigma (DFSS). A methodology that would enable the company to design and build Six Sigma quality into every product and service. Welch committed $200 million dollars to this part of his vision.

In 1997 Jack Welch followed up his 1996 speech with the following "The best Six Sigma projects begin not inside the business but outside of it, focused on answering the question-how can we make the customer more competitive? What is critical to the customer's success? Learning the answer to that question and then learning how to provide the solution is the only focus we need." According to Professor Noel Tichy Jack Welch "set a new contemporary paradigm for the corporation that is the model for the twenty-first century."

In GE's 1998 Annual report the impact from Six Sigma was evident:

- Revenues have risen to $100 billion, up 11 percent.
- Earnings have increased 13 percent, to $ 9.3 billion.
- Earnings per share have grown 14 percent, to $2.80.
- Operating margin has risen to a record 16.7 percent.
- Working capital turns have risen sharply to 9.2 percent, up from 1997's record of 7.4.

This level of performance generated GE $10 billion in cash flow, which helped them to invest $21 billion for 108 acquisitions.

2.2.3 Pioneers of Six Sigma: Dow Chemical

Dow Chemical company is one of the largest sciences and technology companies in the world. Today, Dow services nearly 70,000 customers worldwide in 180 countries. Their product portfolio supplies nearly 3,200 products ranging from food, transportation, health, medicine, personal homecare, building and construction markets. Their annual sales are approximately $33 billion USD. Dow employs approximately 50,000 employees in 38 countries and 208 manufacturing sites [19]. Dow Chemical embarked on its Six Sigma journey in 1999. Their mission is to constantly improve what is essential to human progress by mastering science and technology. With a joint commitment to the triple bottom line of economic prosperity, environmental stewardship, and corporate social responsibility.

According to Antony [19] the road to Six Sigma took shape during a four-month planning period in which the organization focused on bringing about positive culture change as well as higher levels of performance, productivity and values. It was decided this approach would not be a corporate level program to be pushed down the throats of the business units with a lot of responsibility and very little authority. It was agreed upon at the leadership level that for best results the business units would integrate Six Sigma in their respective business strategies. This would place the accountability for success or failure squarely on the shoulders of the company's unit leaders. The initial projects were chosen carefully for maximum impact and these projects delivered significant results that were in line with Dow's Six Sigma's objectives. After this initial success Dow chose to further integrate the methodology and make it their own. In the summer of 1999 Kathleen Bader was named Executive Vice President for Quality and Business Excellence with the responsibility to implement Six Sigma across the all its business units worldwide. Bader further integrated Six Sigma inside of the culture at Dow. She developed an implementation model that consisted of several new perspectives on Six Sigma, including customer and business specific focuses around loyalty and leverage. Figure 2-1 illustrates her model.

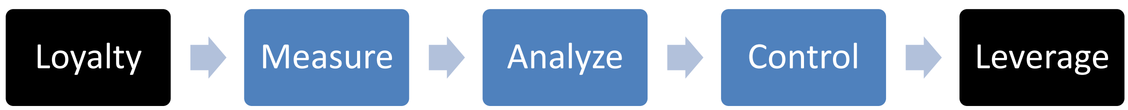

Figure 2-1: Dow Six Sigma methodology

In Dow's approach loyalty was meant to keep the organization loyal to its core values. Dow defines their core values as:

- Loyalty
- Respect for people
- Unity
- Outside-in-focus
- Agility
- Innovation

A major step for Dow on their journey was learning best practices from other companies that have implemented Six Sigma. Two key learnings for Dow were the importance of proper change management and levering best practices across your organization [19]. With this Dow decided to add the leverage step to their implementation roadmap with the intention to take the best practices from previous experiences and use them for current opportunities. More specifically Dow used their central communication system to share best practices across all of their business units. This saved on resources having to reinvent the wheel and sped up the program implementation exponentially. To bring about the needed changes Dow decided to use the staircase of change leadership model. The staircase model consisted of 10 levels, starting with vision and ending with success. The model shown in Figure 2-2 illustrates the staircase of change leadership Dow used to implement Six Sigma. The levels they chose were vision, values, attitude, language, behavior, best practices, articulate strategy, implementation, culture change and success. Each level consisted of given criteria and served as a building block to the next level. Vision: "Dow will become recognized and lauded as one of the premier companies of the 21^{st} century, driven by an insatiable desire to achieve a Six Sigma level of performance and excellence in all we do". Values: Integrity, respect for people, unity, outside-in-focus, agility and innovation. Attitude: Six Sigma is only as effective of the mindset of the people who deploy it. Language: Solution oriented, positive language. Behaviors: Intolerance for variation, measuring inputs and outputs, accountability for all, delivering measurable, sustainable gains, delivering customer satisfaction to build customer loyalty, leverage competitive advantage through information sharing. Best practices: Study previous successes and identify what worked and what did not. Articulated Strategy: Vision, values and strategy, processes and measures of outcomes, organizational culture, information technology and systems, human resource policies. Implementation: Advanced strategic planning and building agility into deployment.

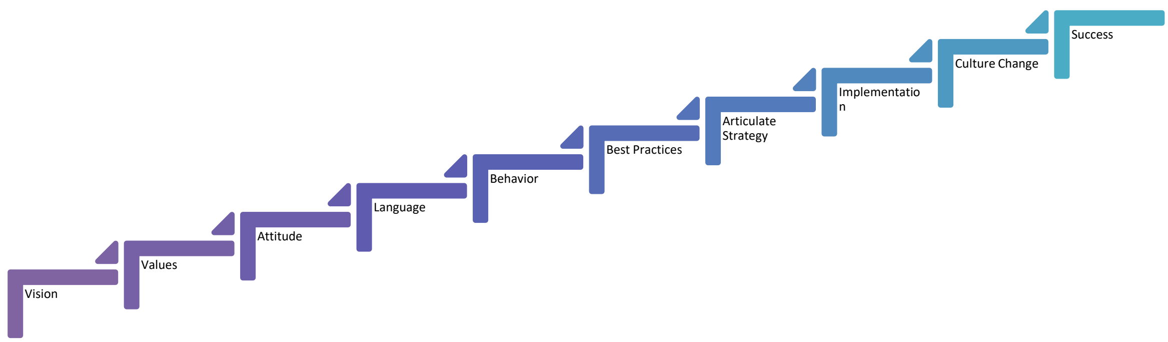

Figure 2-2: Staircase change leadership model

Dow's use of the staircase change model gave them structure to deploy the methodology throughout their organization. Dow relied on an end to end integration approach and it paid significant dividends [19]. Resulting in:

I. 300 Master Black Belts, 1400 full time Black Belts and 2500 Green Belts trained
II. 41.7% employees engaged in successful Six Sigma projects
III. Nearly 3000 projects completed
IV. More than 4000 active projects in process
V. Average estimated project gains = $600,000
VI. Average project completion time = 6 months

VII. The goal of achieving EBIT of $1.5 through Six Sigma is posed for accomplishment one year ahead of schedule

2.2.4 Pioneers of Six Sigma: DuPont

According to Harry and Linsenmann [7], in the late 1990s, DuPont found itself undergoing a seismic shift as the knowledge economy became a driving force in the marketplace. This shift forced DuPont to reinvent its identity and corporate strategy. The 200-year-old DuPont Corporation had come to a crossroad. The oldest industrial company in The Fortune 500 had to decide what it wanted to be for the next 100 years. DuPont had reached a performance ceiling, given the industry it was in, its history, strategy, size and the marketplace in which it operated. It's chemicals and materials businesses were no longer seen as the growth engine of the company, even though they boasted some of the world's best-known creations, including nylon, Teflon, Lycra, Kevlar and Stainmaster. In 1998 DuPont elected Chad Holliday as CEO to lead this overhaul. DuPont had to recreate itself in order to sustain its legacy as one of America's strongest and longest standing corporations. The need for change led Dow to study Six Sigma. At first glance, given its history and culture, the traditionally run DuPont did not it seem to be a likely candidate to take on a radical transformation such as Six Sigma. Through investigating best practices key executives at DuPont came to see what six Sigma had done for AlliedSignal, GE, American Express, Abbott, and many other companies. They decided Six Sigma could take DuPont to a new level and transform the company. Unlike other management initiatives, the goal of Six Sigma is to change the way a corporation gets work done, rather than just tweak the existing system [5]. One of the greatest challenges DuPont faced with introducing and implementing Six Sigma was a general feeling amongst the managers and employees that Six Sigma is yet another improvement program that ultimately would fall by the wayside. Knowing this challenge DuPont set out to pull all resources together in order to develop a comprehensive plan that could help DuPont make this major cultural transformation. DuPont consulted with several industry leaders including Dr. Joseph Juran. Dr. Juran presented his philosophy on the importance of a project by project improvement approach. Stressing a company should have 3000 projects underway to deploy radical change. The advice from Dr. Juran changed the perspective on what it would take to move a corporation the size of DuPont forward. At this point DuPont realized what it had done with its quality program in the past was not what it should have done. Validating that the programs of the past were not pervasive enough to move the business in the right direction. This led DuPont to shift its focus from quality initiatives to improving business fundamentals. The key take-away was the idea from Dr. Juran, many improvement projects could add up to a major change. DuPont contacted industry leaders who have successfully implemented Six Sigma on a large scale. DuPont enlisted the expertise of AlliedSignal CEO Larry Bossidy. In 1998 Mr. Bossidy gave CEO Chad Holliday first hand experiences with deploying Six Sigma, including specific project examples. DuPont also met with GE's then CEO Jack Welch, whose company has successfully adopted Six Sigma as well [7]. Welch confirmed the legitimacy of the examples given by Larry Bossidy as well as business results yielded at GE. Harry’s research suggests at this point DuPont decided that if Six

Sigma worked for AlliedSignal and GE it might work for DuPont. DuPont realized they would need help bring capability and capacity to the surface. Dupont looked to a Six Sigma consultant to help bring about this monumental change. Based on key criteria of becoming self-sufficient in a short time frame and having significant implementation experience DuPont decided the Six Sigma academy was the best choice. The Six Sigma academy was cofounded by Mikal Harry and Richard Schroeder. The Six Sigma academy gave DuPont a structure to implement Six Sigma. Figure 2-4 gives a visual of this structure. In five years, Six Sigma helped DuPont save and earn $2.3 billion dollars.

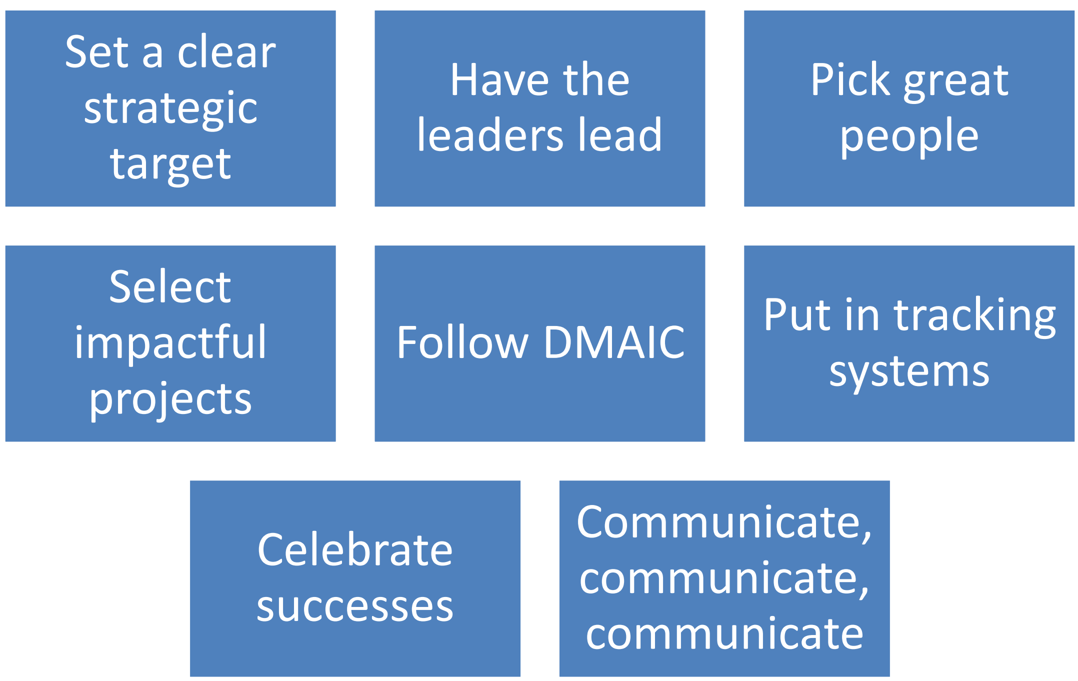

Figure 2-3: Six Sigma deployment structure

2.2.5 Savings from Six Sigma Pioneering Companies

Year	Revenue ($ Billion)	Savings ($ Billion)	Revenue savings (%)
Motorola (1986 - 2001)	356.9	16.1	4.5
Allied Signal 1998	15.1	0.52	9.9
GE (1996 - 1999)	382.1	4.43	1.2
Honeywell (1998 - 2000)	72.3	1.84	1.2
Ford (2000 - 2002)	43.9	1.6	2.3
Dow Chemcial Company (1999 - 2002)	120	1.5	1.25

Table 2-1: Savings from pioneering companies [19]

2.3 Oil and Gas Implementation: ChevronTexaco

According to Buell and Turnipseed [3] in the early 2000's ChevronTexaco implemented Lean Six Sigma in order to improve oilfield operations. According to Scot Buell and Stephen Turnipseed in 2002-2003 ChevonTexaco was able to complete 15 improvement projects that yielded in excess of $500,000 each. In Southeast Asia improvement teams were able to complete 16 projects that yielded $1,000,000 U.S. dollars each. One project focused on improving well testing practices. The process consists of a portable mass-flow/density meter mounted to the back of a flatbed truck. The truck parks next to the wells and connects to a manifold, which allows diversion of the fluid through the meter. Upon data collection and study the team found this process over predicted oil production by approximately 30%. Process analysis identified that the manual input of water density for each well was the largest factor influencing the process. Existing water densities were found to have shifted over time because of waterflood activities. New data was collected by the group and resulted in 22%

improvement in accuracy. Figure 2-3 shows the improvement in test accuracy improvement.

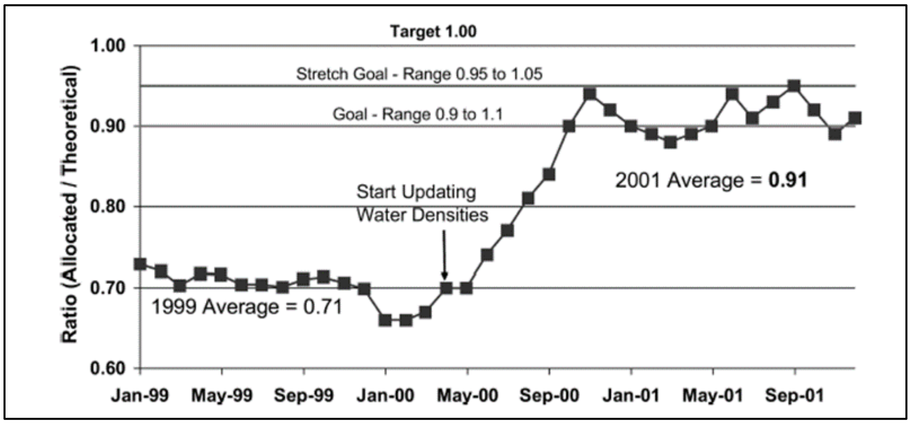

Figure 2-4: Southeast Asia Well Test Accuracy

2.4 Seamless Tube Rolling

According to Buzas [18] a pipe or tube is made of a long hole, surrounded by metal or plastic centered around the hole. The internal diameter (I.D.) of all pipe must not exceed the outside diameter (O.D). The bottom line is a pipe or tube is a bar with a hole pulled through it. The applied research and study of the Mannesmann brothers, Reinhard and Max [4] explains the brothers invented the rolling process for seamless steel tubes in 1885 in their father's file factory in Remscheid. A patent was granted in 1886 and the rolling of the first tubes commenced. By 1889 with the help of various investors the brothers began to manufacture tubes. The Mannesmann process was based on piercing a hole in a solid bar and stretching it out to a desired diameter through large cylinder-shaped spheres. Figures 2-5, 2-6 and 2-7 highlight this process.

This reduction step was coined as the pilger-rolling process. The pilger process was the first major breakthrough from Reinhard and Max. The pilger process was the first documented method to roll a seamless tube. The pilger process forces a hollow tube between two semicircular rollers and gradually reduces the outside diameter without changing the dimensions of the inside diameter. This is achieved by arranging the rollers in a cross pattern instead of the traditional longitudinal direction. The axes of the rolls are arranged in a parallel manner to the stock axis but at perpendicular angle to the stock plane. The rolls roll in the same direction allowing for a helical passage for the stock to pass through the roll gap. The piercing process alone could not produce tubes of normal wall thicknesses in useable lengths and this what drove the creation of the pilger rolling process [20]. This piercing and rolling process together was later known to the world as the “Mannesmann Process”. The Mannesmann process unlocked new potential that revolutionized engineering, piping and vehicle construction for the following decades. The practical experience of Buzas [18] highlights there are several significant benefits of this process, including improved internal diameter (I.D.) quality, better uniformity of the I.D. wall thickness, better control of the hollow length and material concentricity. Controlling variables in the piercing, rolling, elongation and sizing steps reduce variation in these key performance indicators (KPI’s) which improves the probability for a prime product [18].

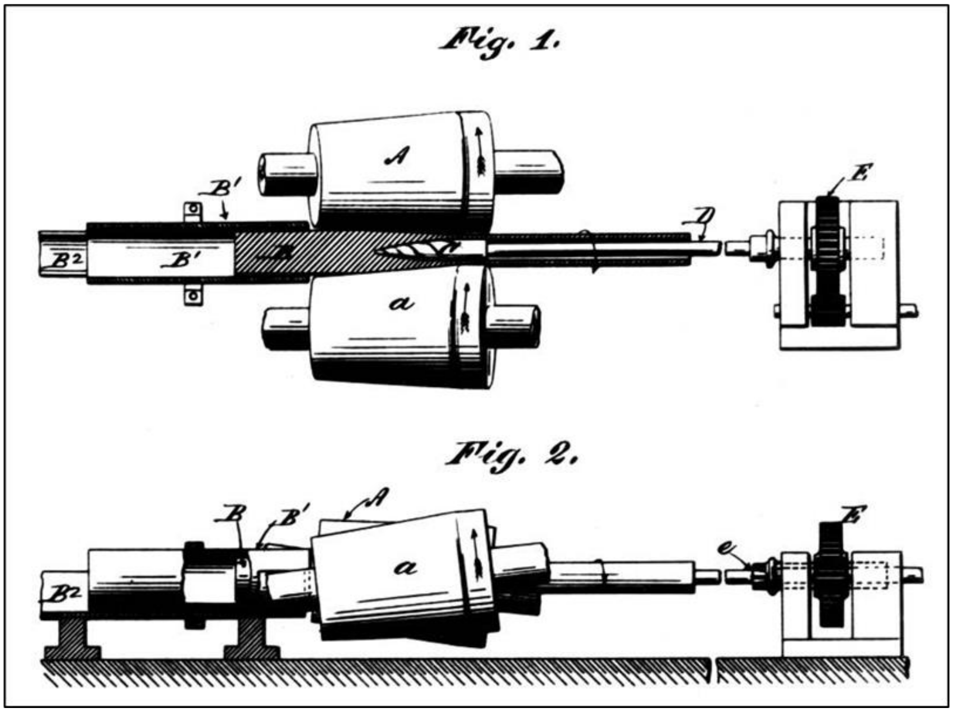

Figure 2-5: Cross rolling configuration for piercing process

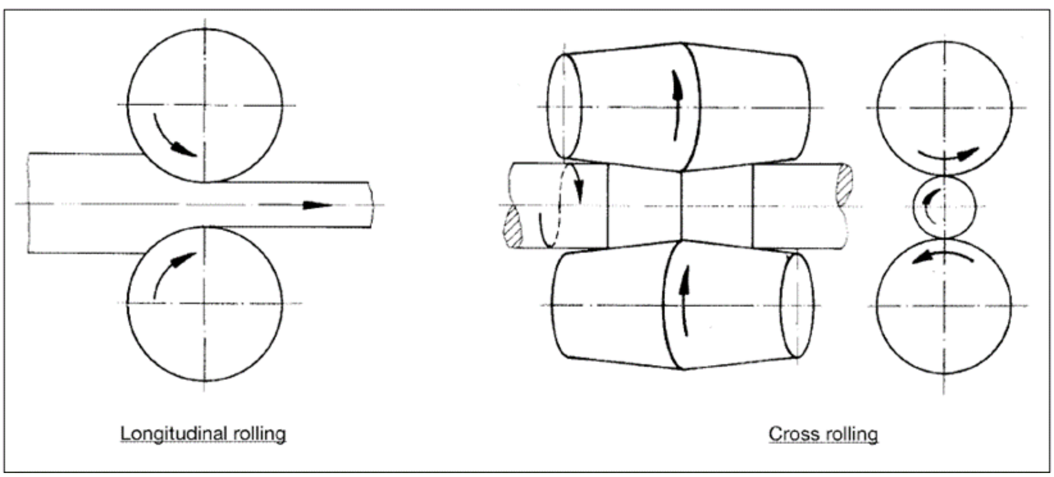

Figure 2-6: Diagram of cross and longitudinal rolling

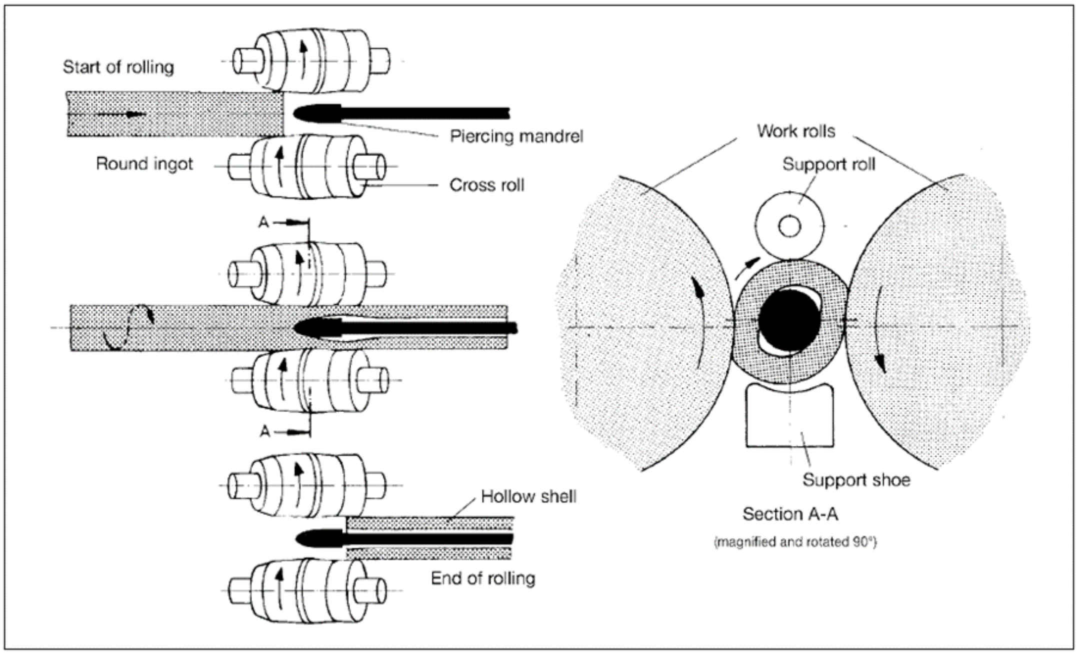

Figure 2-7: The Mannesmann Process

The Mannesmann process paved the way for several advances within the steel rolling community around the turn of the 19th century. The plug rolling process, also known as the “Stiefel Process”, the continuous mandrel rolling process, the push bench process, the pierce and draw process, the tube extrusion process and the Diescher rolling process were all born from the invention of the Mannesmann process [20].

Vallourec Star Youngstown utilizes the continuous mandrel rolling process, more specifically Vallourec Star Youngstown utilizes a Multi-stand Pipe Mill (MPM) and a Fine Quality Mill (FQM) [18]. Figure 2-8 shows the arrangement of mill stands inside of Vallourec. The continuous mandrel mill arranges several graduated rolling passes in tandem inside of rolling stands to form a rolling line. This mill type elongates the hollow shell pierced during the piercing mill over a floating or retained mandrel bar acting as the internal tool to produce the finished tube [20].

Figure 2-8: Mill stands inside of a Vallourec Facility

2.5 Define Phase of DMAIC

The work of Pande, Neuman and Cavanagh [9] articulates the first step of Six Sigma is knowing what your objective is. Your objective has to be clear. Depending on the business environment, the maturity of the organization, level of available resources and ultimately the scale of impact you want to make will lead you to the best start up strategy. This will also give clarity if Six Sigma is the correct methodology for an organization. Six Sigma can be deployed at three levels. Table 2-2 gives the detailed breakdown of each. The first level is business transformation, the second targets strategic improvement and the last is specific to solving a particular problem.

Objective	Description
Business Transformation	A major shift in how the organization works; aka "culture change" Examples: 1. creating a customer focused attitude 2. Building greater flexibility 3. Abandoning old structures or ways of doing business
Strategic Improvement	Targets key strategic or operational weaknesses or opportunities Examples: 1. Speeding up product development 2. Enhancing supply chain efficiencies 3. Building e-commerce capabilities
Problem Solving	Fixes specific areas of high cost, rework, or delays. Examples: 1. shortening application processing time 2. reducing parts shorages in west 3. decreasing volume of past due receivables

Table 2-2: Three levels of Six Sigma objectives [9]

On a business transformation level implementation of Six Sigma there are five core competencies for a successful deployment of Six Sigma [9].

1. **Identify core processes and key customers**
2. **Define customer requirements**
3. Measure current performance
4. Prioritize, analyze, and implement improvements
5. Expand and integrate the Six Sigma System

Of these, the first two steps are aligned with the “Define” phase, the others follow “Measure”, “Analyze” “Improve” and “Control” phases of the methodology.

In step one the key objective is to create a clear, “big-picture” understanding of the most critical cross functional activities in your organization, and how they interface with external customers. The deliverables of this step are a “map” or inventory of value delivering activities in your organization, driven by three questions:

I. What is our core or value adding processes?

II. What products and or services do we provide to our customers:

III. How do processes “flow” across the organization

In step two the key objectives are to establish standards for performance that are based on actual customer input so that process effectiveness and capability can be accurately measured. Customer satisfaction can be predicted and used to develop or enhance systems and strategies devoted to ongoing “Voice of the Customer” data gathering. The deliverables of this step are a clear, complete description of the factors that drive customer satisfaction for each output and process – aka “requirements” or “specifications” in two key categories:

i. “Output Requirements” tied to the end product or service that make it work for the customer (what quality gurus have call “fitness for use”

ii. “Service Requirements” describing how the organization should interact with the customer

The work of Pande, Neuman and Cavanagh explains there are several possible starting points or “on ramps” corresponding to the “Objective” for an organization’s Six

Sigma effort [9]. The top ramp at the business transformation level is for those who have the need, vision and patience to launch a full-scale change initiative. The best approach is to concentrate on developing a map of a few core processes, rather than trying to identify and define all processes at once. The "middle" on-ramp offers the most options. A strategic improvement effort can be limited to one or two key pilot improvements projects, or it can engage a whole wave of teams aimed at addressing a strategic weakness. The third on-ramp is the Problem Solving on-ramp. Most organizations choose to jump to this one first. Pande, Neuman and Cavanagh believe this [9] because it is usually the quickest way to a payoff but doing only problem solving can also be the riskiest shortcut. Due to poor project selection and limited gains.

On a project level in the "**Define**" phase of DMAIC a team refines its problem statement and goal, identifies the customers served by the process being studied, defines customer requirements and writes the plan of how to complete the project [10]. The work of Ellis [21] supports writing a plan. Define sets the stage for a successful Six Sigma project by helping to answer four critical questions [9]:

1. What's the problem or opportunity we will focus?
2. What's our goal? {That is, what results do you want to accomplish, and by when}
3. Who is the customer that is being served and or impacted by this process and problem?
4. What is the process we're investigating?

The deliverables of the define phase are highlighted below in Figure 2-9. Starting with steering committee or leadership approval, an excellent problem statement, a high-level process map and a completed charter.

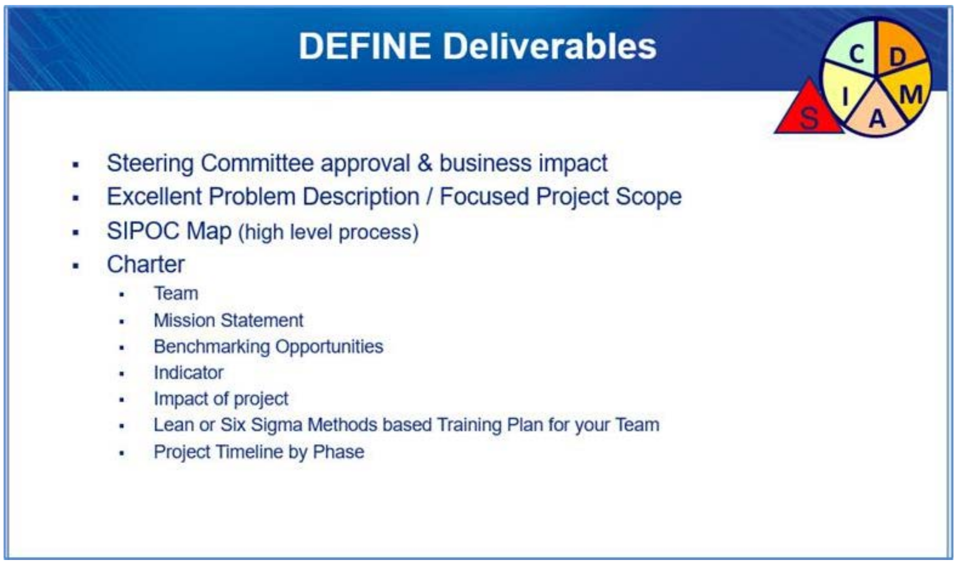

Figure 2-9: Define Deliverables

2.6 Measure Phase of DMAIC

At a business transformation level step 3 "Measure current performance" looks into how well you're delivering on customer requirements today and how likely you are to do so in the future [9]. The key objectives are to accurately evaluate each process's performance against definable customer requirements, and to establish a system for measuring key output s and service features. The deliverables of step 3 are:

I. Baseline Measures – quantified evaluations of current/ recent process performance.

II. Capability Measures – assessments of the ability of the current process/ output to deliver on requirements. These include “Sigma” scores for each process that allow comparison of very different processes.

III. Measurement Systems – new or enhanced methods and resources for ongoing measurement against customer – focused performance standards

As highlighted by Pande, Neuman, and Cavanagh [9] the Six Sigma measure gives you a simple, consistent way to track and compare performance to customer requirements. Measure gives a complete current state view of the business today.

On a project level the “**Measure**” phase of DMAIC reviews the types of measurement systems and their key features [5]. Measure evaluates the metric used to determine how good or bad the problem is and begins the search for root causes. Measure addresses two key questions [9]:

I. What’s the focus and extent of the problem, based on measures of the process and or outputs? (Baseline measure)

II. What key data may help to narrow the problem to its major factors or “vital few”, “Red x’s” root causes?

Figure 2-10 highlights the process funnel concept [11] for segregating Red x’s from other process variables. The entire process is predicated on the postulate that Y is equal to the function of the X’s. Each project has a high-level Y (the desired outcome). All y’s are what they are as a direct result of the X’s influencing them [11]. Figure 2-11 showcases deliverables from the measure phase. A detailed process map, declaration of a baseline indicator, measurement system validation (if applicable), established goals or targets and revisiting the charter page.

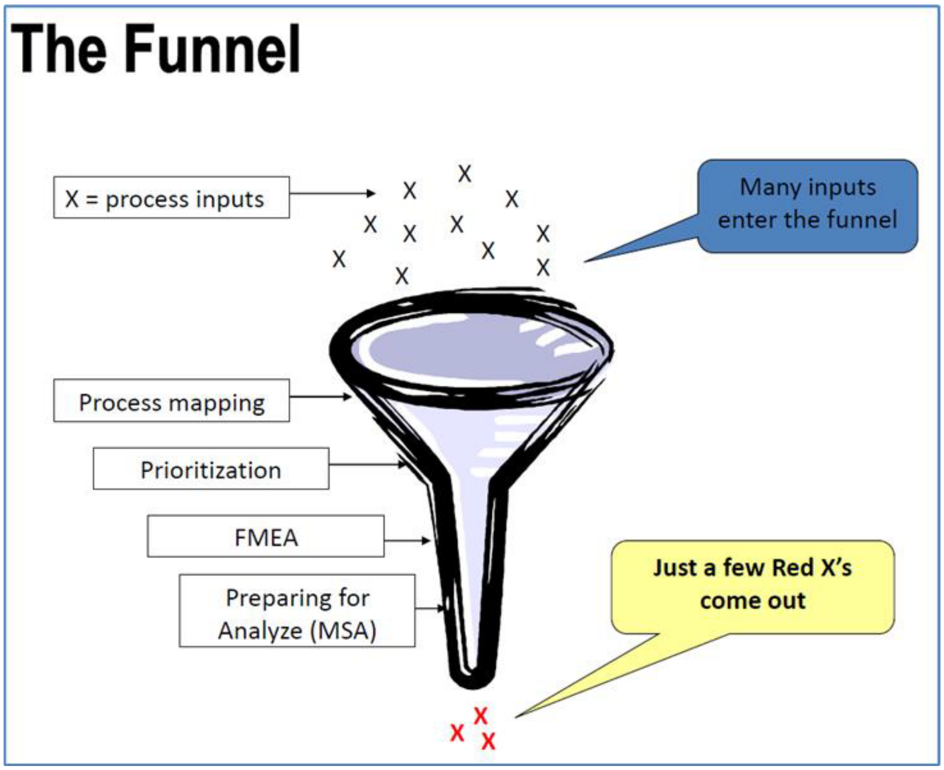

Figure 2-10: Measure Funnel

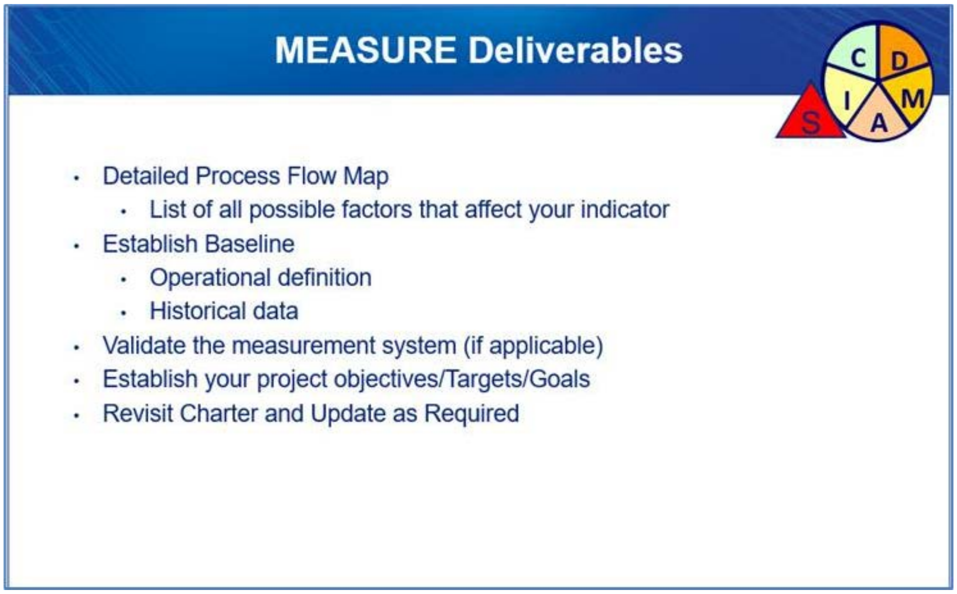

Figure 2-11: Measure Deliverables

2.7 Analyze, Improve Phases of DMAIC

At the business transformation level step 4: Prioritize, Analyze and implement improvements focus on choosing your improvement priorities. The objectives of step 4 are to identify high potential improvement opportunities and develop process – oriented solutions supported by factual analysis and creative thinking. Also, to effectively implement new solutions and processes and provide measurable, sustainable gains [9]. The deliverables for Analyze are:

I. Improvement Priorities. Potential Six Sigma projects assessed based on their impact and feasibility.

II. Process Improvements. Solutions targeted to specific root causes (aka “continuous” or “incremental” improvements).

III. New or Redesigned Processes. New activities or workflows created to meet new demands, incorporate new technologies, or achieve dramatic increase in speed, accuracy, cost performance, etc. (aka Six Sigma Design or Business Process Redesign)

On a project level the "**Analyze**" phase of DMAIC focuses on data and determining the relationships between the variable factors in the process and the direction of improvements. The analyze phase determines how well (or, in many cases, how poorly) the process is currently performing and identifies possible root causes of variation in quality. The data analyzed can reveal the basic nature and behavior of the process, and show how capable and stable the process is over an extended period of time [5]. Pande, Neuman and Cavanagh [9] represent the analyze phase as a cycle highlighted below in Figure 2-12. The goal is to confirm and select the vital few causes. This is accomplished by studying the process and analyzing data. With this information teams form and refine hypotheses. The root cause cycle indicates there are two key sources of input to determine the true cause of your problem.

I. Data Analysis: Use of measure and data to discern patterns, tendencies or other factors that either suggest of disprove possible causes

II. Process Analysis: Deeper investigation into and understanding of how work is being done to identify inconsistencies or problem areas that might cause or contribute to the problem.

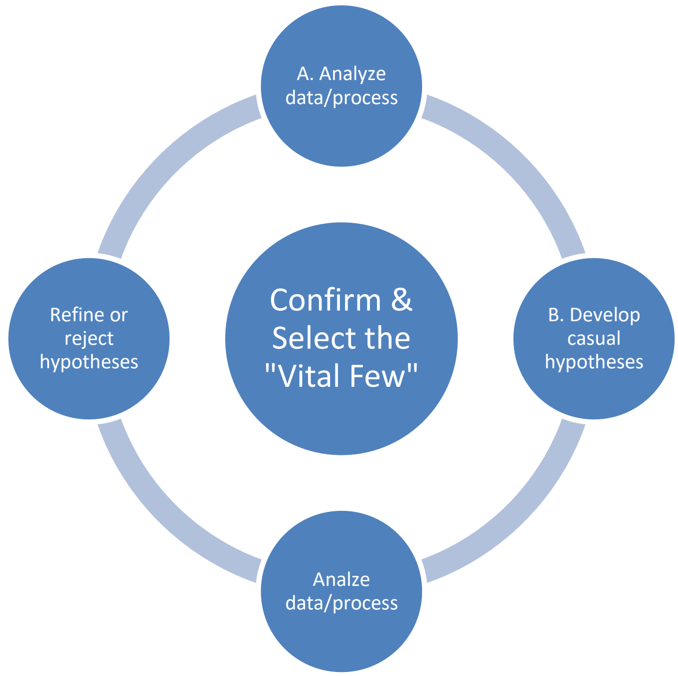

Figure 2-12: Root cause hypotheses and analysis cycle

Analyze will allow teams to develop hypotheses of the root cause(s), to verify causes, form bases for solutions, gain a clear understanding of cause and effect relationships and understand process capability [11]. The tools of Analyze and Implement are clustered in three groups [10].

I. **Exploring**: Investigating the data or process with an open mind, just to see what you can learn.

II. **Generating theories about causes**: Using your new found knowledge to identify the most likely causes of defects.

III. **Verifying or eliminating causes**: Using data, experimentation, or further process analysis to verify which of the potential causes significantly contribute to the problem.

Figure 2-13 highlights the tools best for **exploring** include Pareto charts, run charts and histograms [10]. Tools that aid in **generating theories about causes** include the cause and effect (Ishikawa / fishbone) diagram, box plot, 5 whys, and prioritization matrices. The tools that help to **verify or eliminate causes** include correlation studies, regression, hypothesis testing (Analysis of Variance (ANOVA), T-test, Z-test, Chi-square) and Design of experiments (DOE) [11]. A very important point of the Analyze phase is to match the tool to the problem.

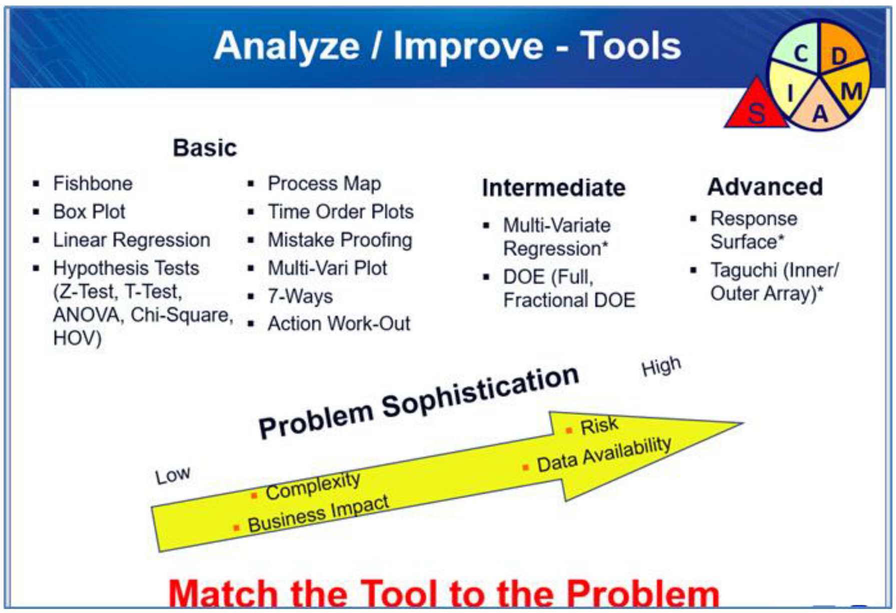

Figure 2-13: Tools of Analyze and Improve

On a project level the "**Improve**" phase of DMAIC focuses on finding and implementing solutions that will eliminate the causes of problems, reduce variation in a process, or prevent a problem from recurring [10]. As highlighted above the power tools of Six Sigma are shared between the analyze and improve phases. Pande, Neuman and Cavanagh [10] support there are five steps in the improve phase:

I. Generate create solutions
II. Cook the raw ideas
III. Select the solution
IV. Pilot test
V. Implement full scale

After completion of these five steps the project team should have led the full-scale implementation of a solution that was clearly linked to root causes of the targeted problem. Figure 2-14 shows the deliverables of the improve phase.

I. A list of possible solutions
II. A list of best solutions
III. Develop an action plan to implement the best solutions
IV. Validation of the implementation
V. Review the project charter if necessary

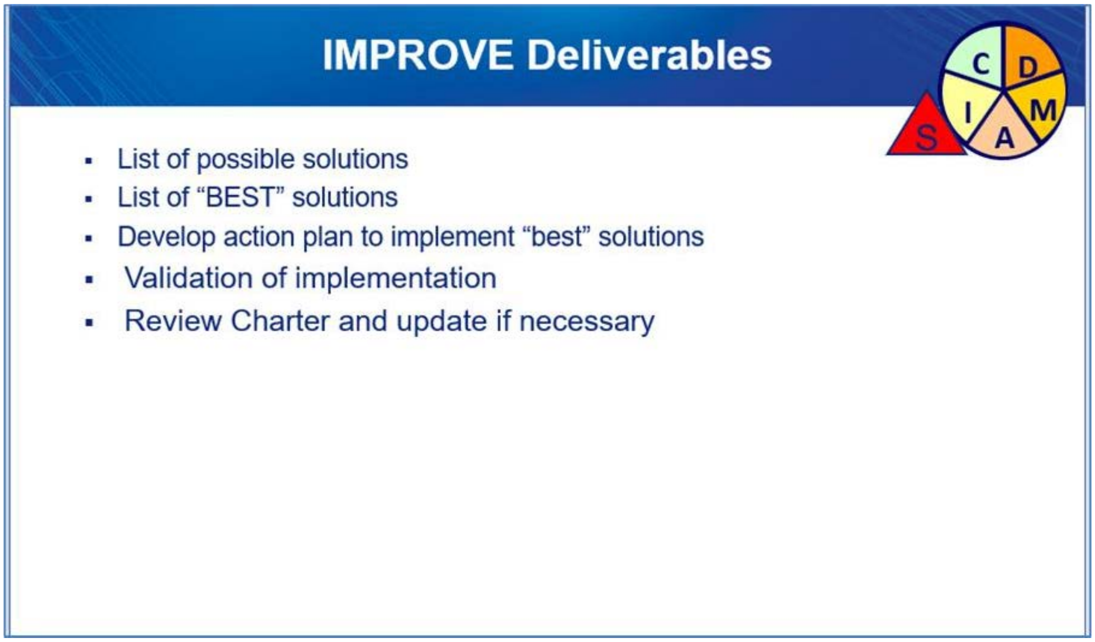

Figure 2-14: Improve deliverables

2.8 Control phase of DMAIC

On any level of deployment, the **"Control"** phase of DMAIC ensures that the same problems do not reoccur by continually monitoring the processes that create the product or service [5]. Without control efforts, the improved process may very well revert to its previous state, undermining the gains you thought you'd achieved and making your work for naught [10]. The control phase has four parts:

I. Discipline
II. Documenting the improvement
III. Keeping score: establishing ongoing process measures
IV. Going the next step: building a process management plan.

The deliverables of control are:

I. Proof of success

II. Standards in place

III. Communications deployed

IV. Project closure

V. Celebrate

Figure 2-15 highlights the deliverables of the control phase. These include provide proof of successful implementation (through results and impact), ensure standards are in place (blocked actions, new documented processes, visual management, audit plan), an effective communication plan in place (postings, steering committee), a formal closure of the project and celebrate the successes of the team(s).

Figure 2-15: Control Deliverables

2.9 Advancement of Research

Six Sigma has been a driver for many organizations for over three decades with the focus to significantly reduce defects inside of their organizations. My research will contribute to the Industrial Engineering field by organizing several “how to guides” and successfully implementing this methodology in the Oil and Gas industry. As of today, there are not many practical examples of Six Sigma being implemented in the Oil and Gas industry. This study will advance the scientific knowledge on how to properly implement this methodology in this industry and others. This study will also target to share conclusions on how to tailor the approach based on factors such as improvement maturity and available resources. In addition, this study will share best practices on how to sustain gains to a specific project and to further deploy the method beyond a project approach. Lastly, this study will reveal how Six Sigma was successfully deployed to solve a quality issue inside of a seamless tube mill.

Chapter 3 RESEARCH AND METHODOLOGY

3.1 Introduction

During the rolling process in Vallourec Star's MPM mill, tubes are subjected to extreme temperatures and major deformation. Figure 3-1 highlights the process steps of the hot rolling process inside of Vallourec Star's MPM mill. The rolling process begins with billets being charged inside of a billet reheat furnace at ambient temperature. The billets then go through a series of heating zones to uniformly heat the billet from outside, in. Next the billets are pierced at the piercing mill. This is the start of the Mannesmann process mentioned during chapter 1. The piercing process creates a hollow shell, that has a rough geometry for a range of pipe sizes. The shells are then rolled in the multi-stand mill, where the hollow shells are then formed to meet specific I.D. and O.D. specifications. The tubes are then stretched in the sizing mill to reach final dimensional specifications and to meet a specific length requirement. Lastly the tubes are cooled in a multistage cooling process with the tubes finishing at room temperature. During the cooling process tubes undergo several metallurgical transformations. Starting as austenite, the tubes transition through the ferrite, pearlite and bainite phases. The cooling process consists of three stages. First the tubes are air cooled on a rotating cooling table. Second the tubes are then transferred to the hot finish area by conveyor and lastly, they water cooled on a rotating cooling table.

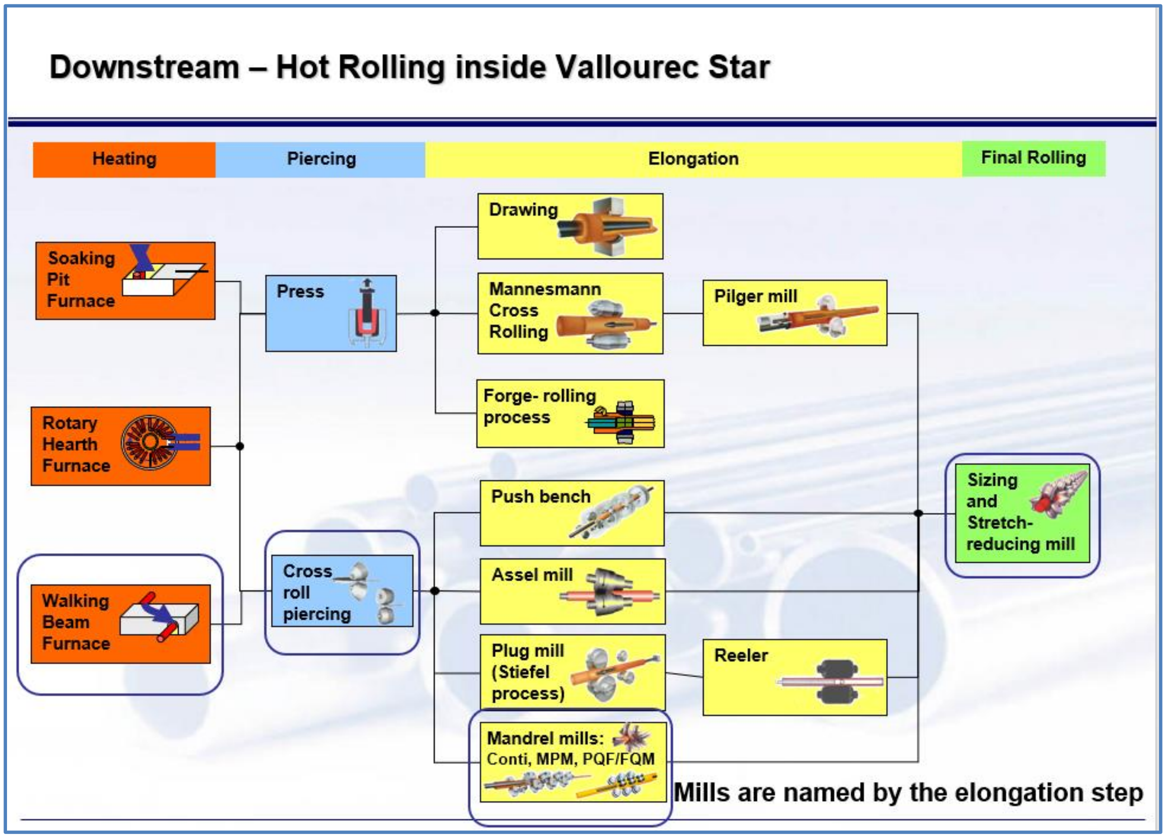

Figure 3-1: Hot rolling process at Vallourec Star's MPM

Note: The outlined boxes highlight the steps inside of the MPM.

The cooling process introduces additional stresses for the tubes. If tubes are not cooled uniformly, they are susceptible to bowing. A bowed pipe is a tube that is unevenly cooled which causes it to distort and bow in various directions. This causes the tube to stop moving along the process and results in a partial or complete shutdown of upstream pipe operations. Figure 3-2 gives a visual of a bowed pipe reject. Each pipe in process has to be craned out of the process and scrapped due to unfinished processing. One bowed pipe can stop the entire rolling process and delay new tubes from exiting the reheat furnace. Resulting in as many as 100 in-process tubes becoming scrap. The rolling process is time and temperature dependent at each process step. Once billets are discharged from the BRF the process becomes a single piece flow operation until pipes are saw cut before the cooling process. Meaning only one tube is processed at a time through the piercing, forming and sizing processes. The reheating process and cooling processes are batch operations.

Figure 3-2: Bowed pipe during cooling process

The complexity of the pipe process offers a great potential for improvement in reducing bowed pipe related defects. The manufacturing process within Vallourec Star is data driven, having data readily available offers a great foundation for the Six Sigma methodology and statistical analysis. The main objectives of this research are to:

1. Quantify cost impact of bowed pipe rejects

2. Form a working team focused on finding the root cause(s) that utilizes the DMAIC methodology as a guide
3. Develop both high level and detailed process maps of the current state process
4. Identify all process variables during the rolling process
5. Utilize statistical analysis to determine the vital few process variables that contribute to causing bowed pipe rejects
6. Develop blocking actions that will lead to solutions and significantly reduce bowed pipe rejects

3.2 Identifying the Need (Define Phase)

The deliverables of the "Define**"** phase of DMAIC are to create the problem statement, to identify the goal of the project, to identify the impact to the business, define customer requirements and write the plan of how to complete the project. To justify the project need several analyses were conducted to quantify potential opportunities around scrap losses inside of Vallourec Star. Figure 3-3 and 3-4 highlight losses due to yield cost Vallourec Star around $30 million in 2011. Out of this $30 million the MPM contributed $4.3 million. Out of this $4.3 million, cobble loss accounted for $547k. Vallourec Star classifies all physical pipe defects as cobble loss. The term cobble loss is equivalent to a scrapped tube. Bowed pipe is classified under the cobble loss category. Bowed pipe accounted for $370k of the $547 inside of the cobble loss category. Bowed pipe was identified as an exceptional candidate for a Continuous Improvement Team (CIT) project based on six criteria: current in-house expertise, data availability, a real problem exists without a known solution, potential cost savings, potential added mill capacity and the need of cross functional effort. These factors led the Steering Committee to recommend chartering an improvement effort to improve the current situation.

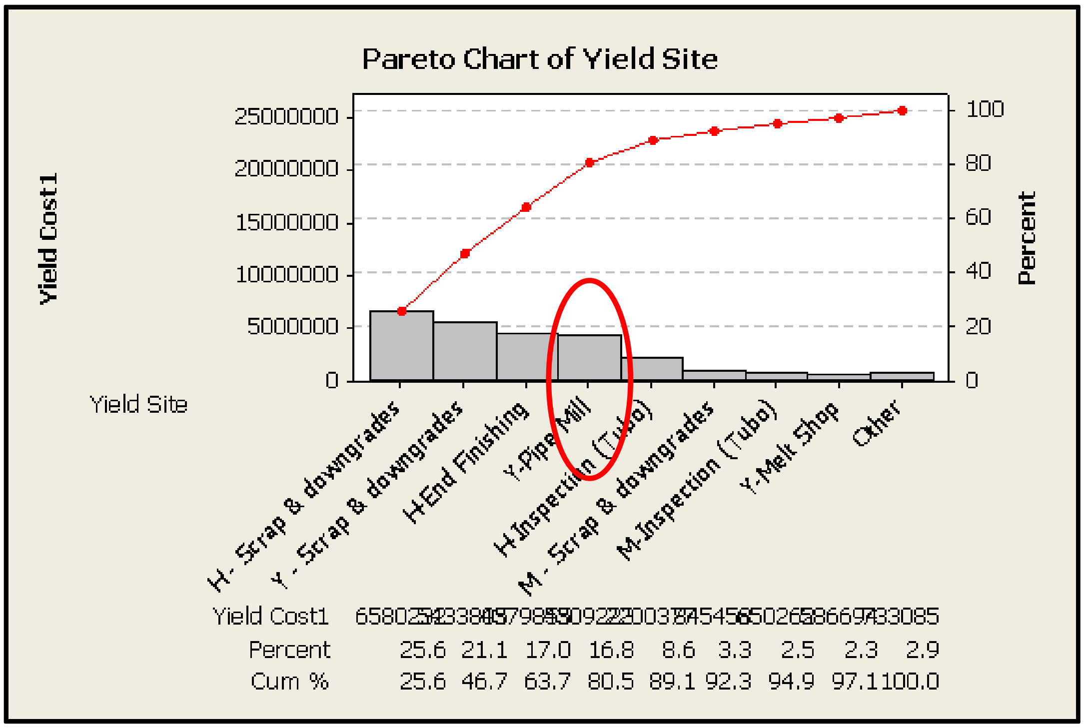

Figure 3-3: Pareto chart of yield loss per site

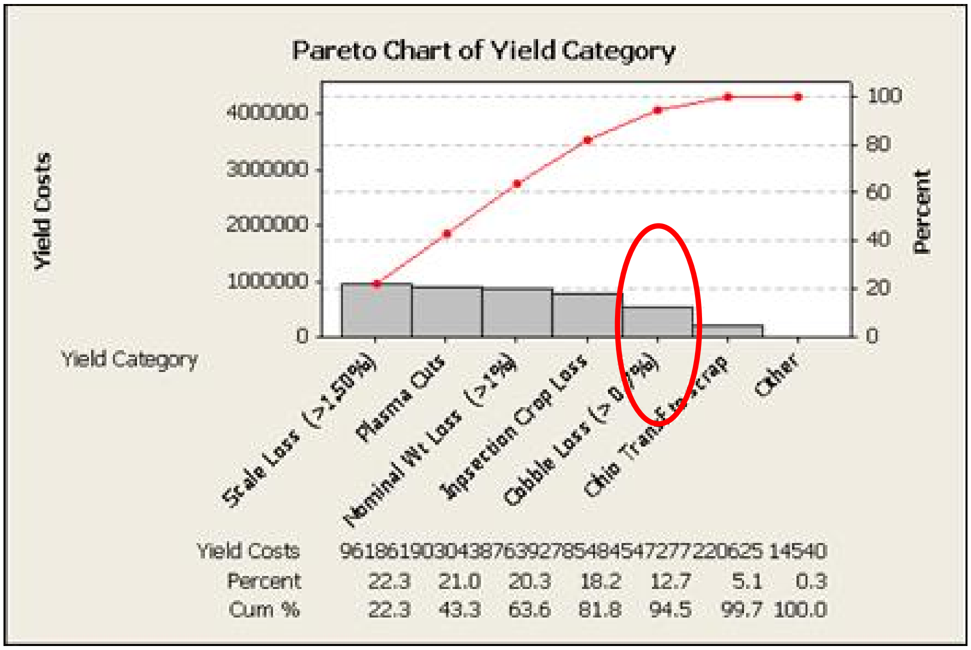

Figure 3-4: Pareto chart highlighting the yield categories inside of the MPM

Following the recommendation of the Steering Committee (SC) and the DMAIC methodology the next step of this project was to create an improvement team to address this effort. Figure 3-5 outlines the deliverables used to navigate the DMAIC methodology. Note: Vallourec has modified the “Improve” & “Control” phases but the deliverables and tools are the same.

Phase	Deliverable		Tools
Define	☐	Obtain Steering Committee Approval	SC review
	☐	Problem Description / Project Scope	Problem Statement/Description - CIT Tracker
	☐	Charter	Charter - CIT Tracker, Review Roles and Responsibilities
	☐	SIPOC Map (high level process)	SIPOC Process Mapping - CIT Tracker, Photos
	☐	Customer Focus - ID customer	VOC/CTQ Matrix, Feedback, Surveys
	☐	Training Plan	Training Plan - CIT Tracker
	☐	Impact Assessment (Financial Approval)	Savings Calculation - CIT Tracker
	☐	Project Timeline by Phase	1-Page Summary - CIT Tracker
	☐	Completion of 1-page summary	1-Page Summary - CIT Tracker
Measure	☐	Detailed process map	Process Map, Photos
	☐	Establish Baseline for the indicator	Time Series Plot
		- Operational Definition of metric	Clearly define the unit and what is considered a defect
		- Historical evolution of metric	Time Series Plot
		- Develop data collection plan if needed	Use if data currently does not exist.
	☐	validate the measurement system	MSA - GRR, Test/Retest
	☐	List of potential x's	Brainstorming/Fishbone, FMEA, Process Inputs/Outputs, Pareto
	☐	Revisit and revise Define/Charter	
Analyze	☐	List of "Vital Few" X's (Red X's)	Prioritization Matrix, 5-why's, Process Inputs/Outputs, DOE, Trials
	☐	Develop theories aimed at resolving problem	Boxplot, Control charts, probability plot, Capability Analysis, normality test
	☐	Revisit and revise Define/Charter	
Implement	☐	List of possible solutions	7 ways, Brainstorming, Trystorming
	☐	List of best solutions	Prioritization Matrix, voting, difficult/ease matrix
	☐	Develop action plan to implement "best" solutions	Action Plan
	☐	Develop Proof of implementation	photos, results
	☐	Revisit and revise Define/Charter	
Check and Standardize	☐	Show evidence of improvement/Proof of success	Indicator, Graphs, Charts, Diagrams, Statistics, Tribal Knowledge
		- confirm results with indicator	Boxplot, Control charts, probability plot, Capability Analysis, normality test
		- confirm impact - Financial Approval	Savints Calculation, CIT Tracker
	☐	Standards are in Place	
		- New process map	Process Map
		- documentation updated/created	Block Actions, FMEA, Standards, control charts, mistake proofing
		- photos and visual management in place	Visual Factory, Training, Audits
		- audit plan developed and scheduled	
	☐	Communications are completed	
		- Posting updated	
		- Sponsor and Steering Committee Briefed	
		- Benchmarking opportunities defined	
	☐	Project Closure	Closure Form
	☐	Celebrate	

Figure 3-5: DMAIC deliverables for a project

The DMAIC roadmap led the team to define needed team members and the scope. The Supplier, Input, Process, Output and Customer (SIPOC) process was used to accomplish this. The selected team was composed of three assistant pipe mill team leaders, four process engineers, a sizing mill operator, the pipe mill general supervisor, all of the pipe mill team leaders and the hot finishing team leader. The Pipe Mill Manager was selected as the project Champion (Sponsor). The cross functional team gave a wide range of experience and process diversity. This experience and diversity were beneficial in solving the problem. The team relied on the help of the process engineering team in the Steel Plant (Melt Shop) on material related topics. With the team in place the first exercise was to validate the problem description, the indicators and to create the cost benefit analysis (CBA). The project charter in Figure 3-6 shows the output of these efforts. The key points of the charter include: The start date, the targeted end date, the meeting frequency, what the team will measure to support success (primary and secondary indicators), a baseline for the indicator, a target for the indicator, the expected savings and the team members involved. After the team defined its scope. The team chose to prioritize investigating high alloy grade products based on the expertise of the team. The high alloy grades inside of Vallourec Star are grades that have a higher content of alloying metals, such as molybdenum, chromium, nickel, silicon and manganese. The selected products are grade 54, grade 57C and grade 59. These products were selected because the majority of defects encountered were due to these three grades. By selecting just three grades the team was be able to minimize any scope creep. After basic data analysis the team was then able to finalize its indicator, establish a baseline, set improvement targets and to forecast a proposed date of completion. The selected indicators are. First, overall cobble loss due to bowed pipe per rolling cycle. Second, delay time associated with handling of bowed pipe. A rolling cycle is the period for the mill to complete one cycle of its product offering, one cycle typically lasts 42 days. The baseline was selected from the first five rolling cycles of the year. The baseline indicators and period are shown in figures 3-7a and 3-7b. A bowed pipe reject is defined as a pipe that cannot be processed in entirety due to the inability to physically move from process to the next. The pipe mill scrapped 440 tons due to bowed pipe rejects during the first five cycles, generating an average of 88 tons/cycle. The mill produced a total of 23,186 high alloy tubes of which 277 were scrapped, resulting in a 1.19% defect rate. With the help of the controlling organization the group was then able to quantify the overall cost impact from the baseline and proposed improvement targets. Due to a high material cost this project will have a significant impact on the overall success for Vallourec Star. With an aggressive reduction target of 70% the potential cost savings for the team are $238,392. A 70% reduction target allows for 26 tons of scrap per cycle. The last aspect of the define phase the team explored were benchmarking opportunities. The team focused their benchmarking efforts around two questions. First, are there other Vallourec facilities experiencing these problems? Second have there been similar improvement efforts pursued in the past? The group contacted the Corporate Research and Development team and found answers to these questions. This issue is common to all Vallourec mills. The group also learned no one within Vallourec has been successful in fixing this issue, so the findings from this research could result in company best practices.

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CIT CHARTER

Annexe D1 PG/DQ-27

Vallourec&Mannesmann V&M STAR

UNIT *(Dept)* : **Pipemill** Entity : **V&M Star** *(Facility Location)*

CIT NAME : **Bowed Pipe CIT**

GROUP **START** DATE: 21-Jul-11 Revision date : 3-Oct-12

GROUP **TARGET** DATE: 30-Oct-12

MEETING

PLACE For The Meeting : **VPA office**

FREQUENCY : **2** a month

TARGET

Indicator	Calculation mode	TQM	Reference 2011 (Cycles 1-5)	Target	Deadline	Expected savings
Cobble Loss (Tons) due to bowed per rolling cycle	Tons/ Cycle		440	70% reduction	10/30/12	$ 238,392
Delay Time	Minutes		81 mins/month	41 mins/month	10/30/12	$ 11,317.33

TEAM MEMBERS

Conductor *(Group Leader)*

- The mission of this team is to reduce loss of cobble due to bowed pipes for special alloy grades (54, 57c and 59)
- Key benefits will be PM Yield and Cost

TEAM MEMBER NAME (Last name, first)	TITLE / POSITION	SIGNATURE
Light, Jeff	PM TL	
Bowers, Randy	Sizer Operator	
McClimans, Jim	ATL	
Buzas, Paul	Senior Rolling Engineer	
Kettler, John	PM Straightener Supervisor	
Powell, Chris	PM General Supervisor	
Spice, Jason	Process Engineer	
Burks, Rene	Process Engineer	
Miller, Ken	ATL	
Allen, Bill	Sizer Operator	
Cunningham, Chris.	VPA	
Howell, Clarence	VPA	
Mazur, Nate	Process Engineer	

Entity General Manager: Signature
Shuster, Eric

Unit Manager : Signature
Francis, Garrett

Entity CIT Leader *(Coordinator)* : Signature
Howell III, Clarence

CIT Sponsor: Signature
Powell, Chris

Figure 3-6: Team Charter for the Bowed Pipe CIT

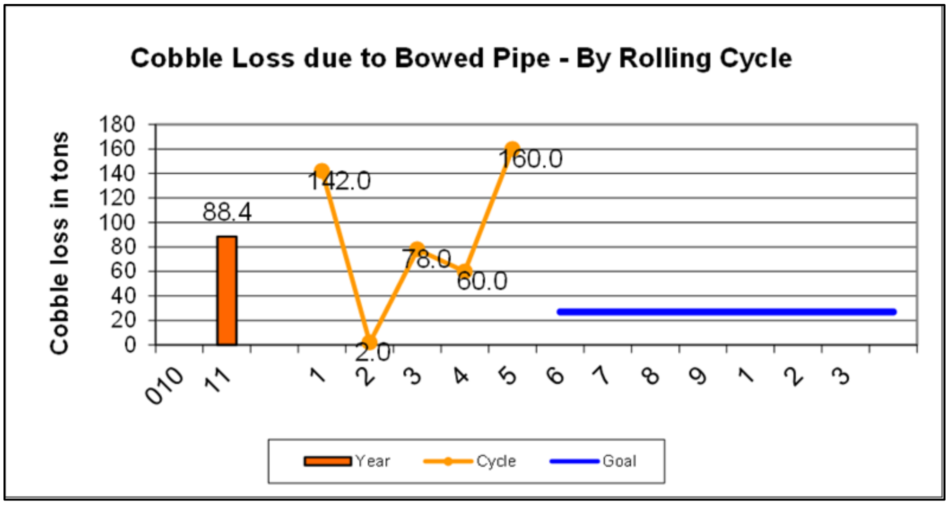


Figure 3-7: Primary indicator for bowed pipe CIT

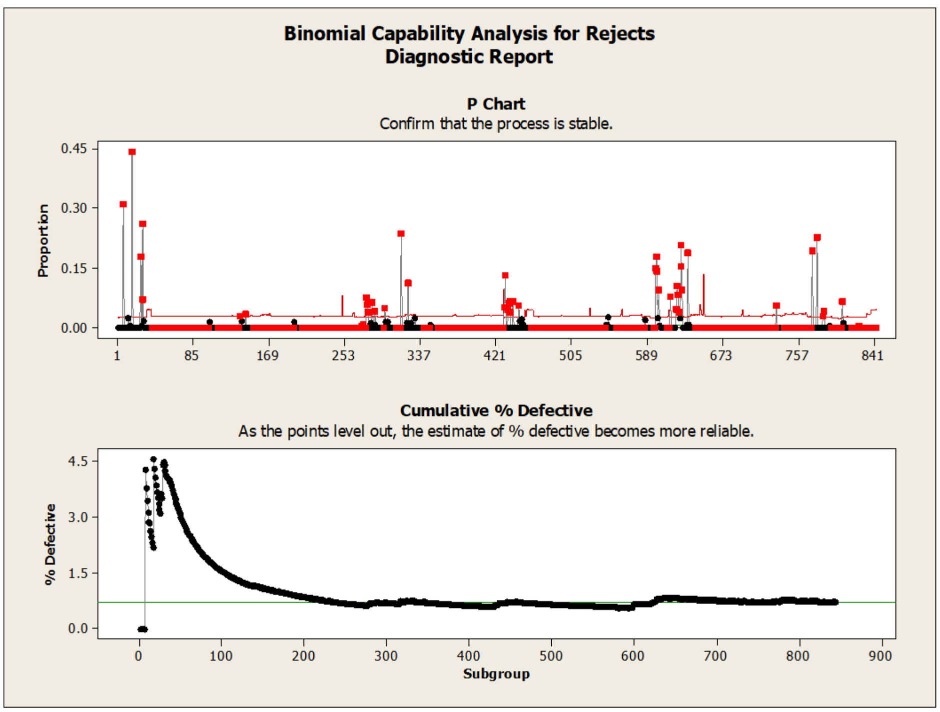


Figure 3-8: Primary indicator data shown in % defective

With the charter created the team drafted an opportunity statement and shared it with the Steering Committee. "Throughout 2011 - 2012 the MPM has encountered cobble losses of up to 6% due to bowed pipes containing high alloy grade materials.

Some manufacturing lots have scrapped up to 45% of pipes due to this phenomenon. Cobble loss due to bowed pipe is a common issue inside of Vallourec mills so if a solution is found possible benchmarking opportunities exist." The mission of the team is to research and implement tools and procedures to reduce cobble loss due to bowed pipe in Youngstown's pipe mill. The team met the deliverables for the Define phase of DMAIC and was given the green light to proceed.

3.3 Process Analysis (Measure)

The primary deliverables of the "Measure" phase of DMAIC are to generate a detailed process map, establish a baseline for your indicator and to identify X's and most importantly Red X's. This process brought together operator expertise (tribal knowledge) from team members, data from the process, and the statistical tools of Six Sigma. The process analysis method was used to identify all needed data and where the information is stored. Supported by the research and implementation of Ellis. The group compiled a list of important input and output factors.

- **Input factors**: Standard operating parameters and pipe dimensions, actual pipe parameters and dimensions, customer requirements
- **Output factor**: Pipe rejects

Next a swim lane chart was constructed to see where each type of data was generated. Figure 3-9 illustrates the swim lane chart for bowed pipe data. The swim lane activity revealed that all needed data came from different systems. For data to be useful, a common data file was created and include all important information.

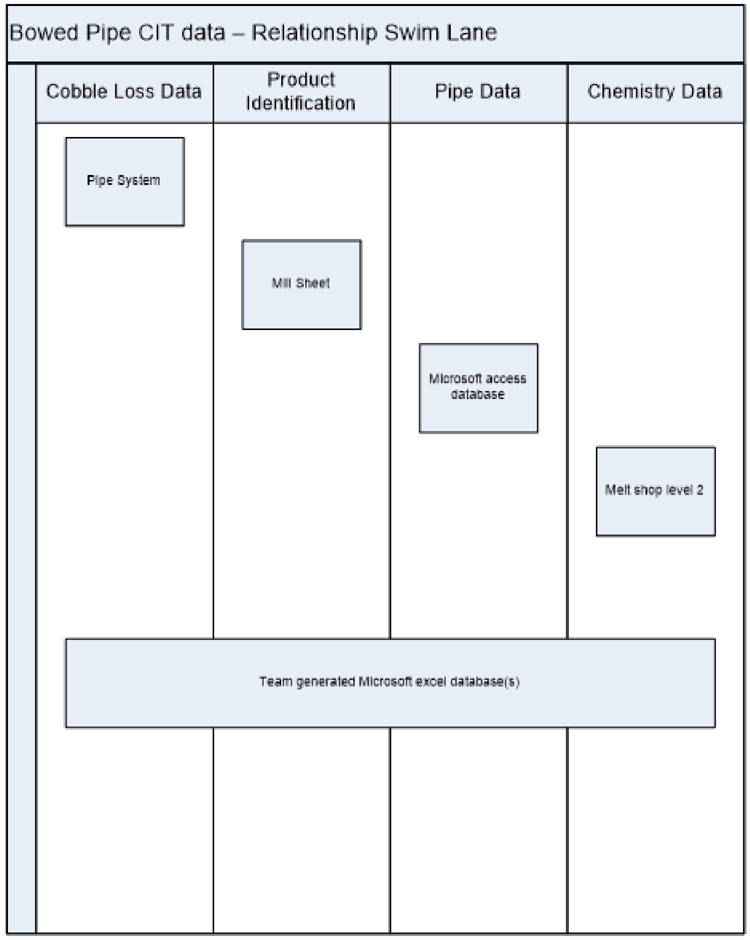


Figure 3-9: Bowed Pipe data relationship swim lane

The team utilized this information and the information from the first SC review to construct 3rd and 4th level Pareto charts to understand how significant the high alloy impact was to this reject. Furthermore, the team generated another Pareto in order to distinguish which high alloy product was the most difficult for the mill to roll. As shown in Figure 3-10 the pareto analysis highlighted that high alloy products generate 80% of bowed pipes rejects while the low alloy materials only contribute 20%. This supports the qualitative analysis from the team. Figure 3-11 then shows that grade 59 is the largest contributor of bowed pipes followed by grade 57C and grade 54.

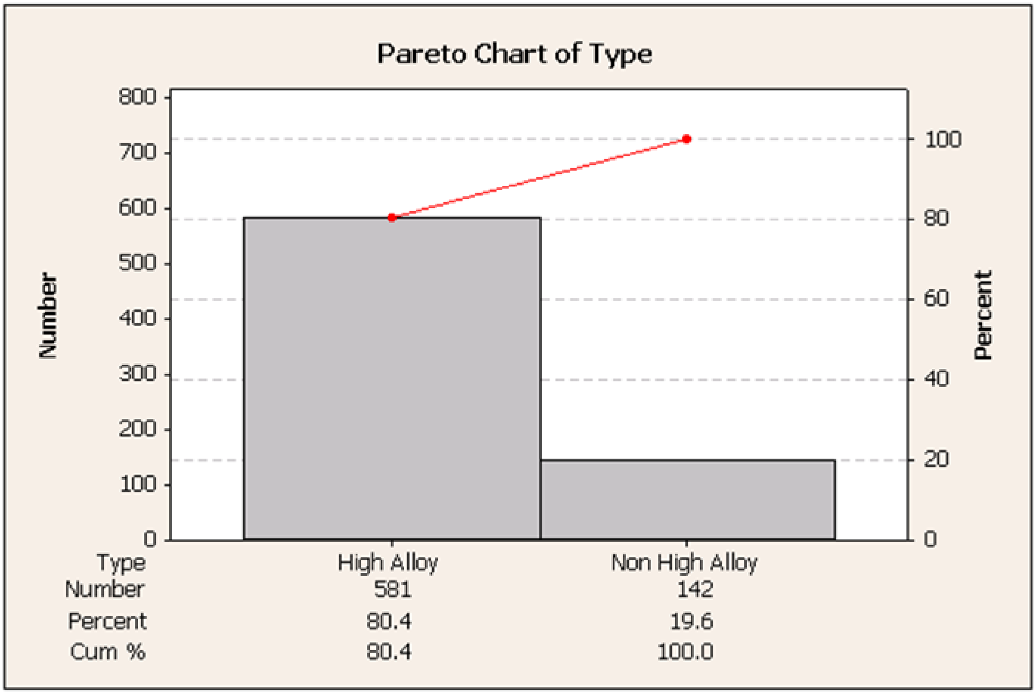


Figure 3-10: Pareto analysis of High Alloy vs. Non-High Alloy grades

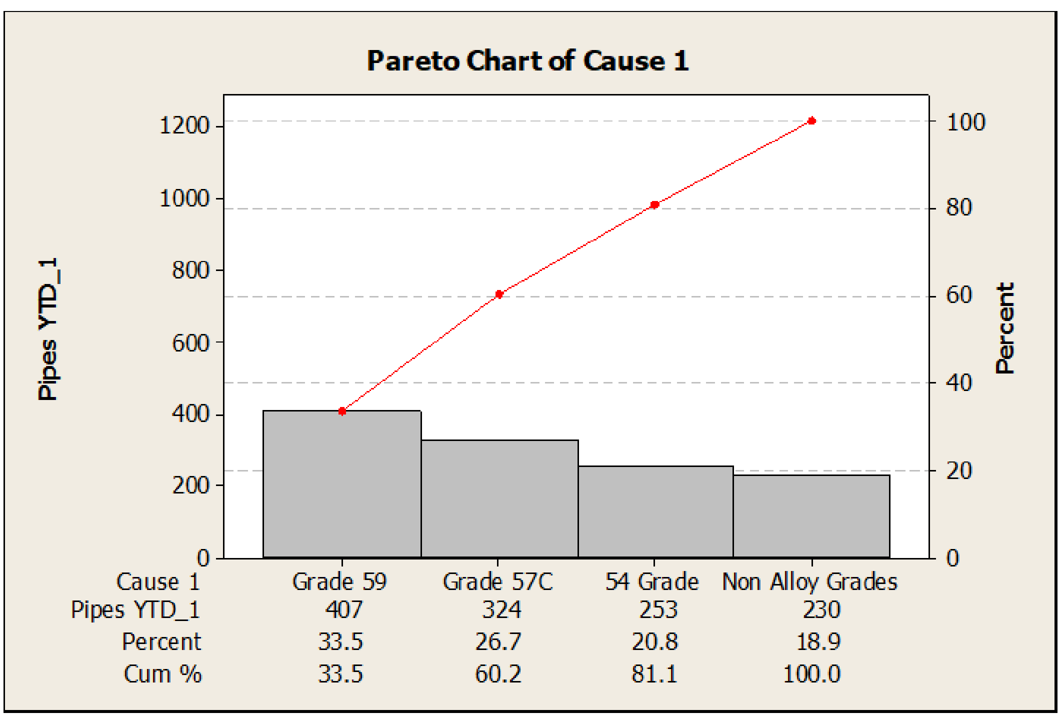


Figure 3-11: Pareto analysis of 3 main High Alloy grades and all Non-High alloy grades

The team utilized this data to establish the baseline for the project and to set up the reporting process. Several Microsoft Excel based data files were then created. Table 3-1 gives a snap shot of the main data file and its contents. The data file includes the product description, the cycle tubes were rolled, the number of tubes rolled per order, the number of rejected bowed tubes and the percentage of rejects on each order.

BON	Recipe	OD	Aim Wa	Grade	Heat no	Billet code	Insp	SLN	Rounds	Pipes	Rejects	Tons	Cycle	Year	Reject Percentage
12030103	C0361V02.CQA	5.5	0.361	102	1214900	BW4	FF	B50223	51	204	1	0.492255	4	2012	0.5%
12020102	C0415?02.CQA	5.5	0.415	102	1210190	r/w4	mp	B50326	42	168	1	0.555595	4	2012	0.6%
12040006	C0415?59.TQA	5.5	0.415	59	1222740	r/w1	mp	B50383	48	192	1	0.525	4	2012	0.5%
12040004	C0415?59.CQA	5.5	0.415	59	1219050	b/w3	mp	B50442	48	192	1	0.529375	4	2012	0.5%
12020010	C0476W59.TQA	5.5	0.476	59	1207220	R/W4	JT	B50481	39	156	1	0.610385	4	2012	0.6%
12040000	C0476W59.TQA	5.5	0.476	59	1224840	B/W6	FJF	B50483	45	180	1	0.610389	4	2012	0.6%
12040019	F0280U61.LPA	6.625	0.28	61M	1219730	w/b3	mp	B60015	60	240	1	0.42875	4	2012	0.4%
12040051	N0472K02.CQA	9.625	0.472	102	1221130	b/w5	c	B60204	21	84	3	2.627857	4	2012	3.6%
12030105	C0304U02.HQA	5.5	0.308	102	1218240	w/b4	c	B60230	60	240	1	0.417875	5	2012	0.4%
12040101	C0304U02.HQA	5.5	0.308	102	1220290	BW2	FF	B60234	57	228	8	3.34302	5	2012	3.5%
12050001	C0415?59.TQA	5.5	0.415	59	1223870	B/W3	FJF	B60319	48	192	3	1.575	5	2012	1.6%
12050001	C0415?59.TQA	5.5	0.415	59	1223880	R/W4	FJF	B60320	48	192	2	1.05	5	2012	1.0%
12050001	C0415?59.TQA	5.5	0.415	59	1225120	RW5	FF	B60339	51	204	2	1.05	5	2012	1.0%
12050001	C0415759TQA	5.5	0.415	59	1225000	B/W1	JM	B60344	51	204	2	1.05	5	2012	1.0%
12150002	C0415?02.CQA	5.5	0.415	102	582049	W/R4	LM	B61315	140	560	1	0.554375	5	2012	0.2%
12060050	C0415?54.DQA	5.5	0.435	54	1230270	b/w6	mp	B70006	57	228	3	1.299342	5	2012	1.3%
12060050	C0415?54.DQA	5.5	0.435	54	1230260	W/R2	LM	B70008	59	236	4	1.732542	5	2012	1.7%
12050048	C0415?59.CQA	5.5	0.415	59	1228570	R/W1	JM	B70025	51	204	3	1.588088	5	2012	1.5%
12050048	C0415?59.CQA	5.5	0.415	59	1228600	B/W3	JM	B70027	48	192	12	6.304375	5	2012	6.3%
12050042	$0625E54.CQB	9.875	0.625	54	1226560	r/w1	mp	B70119	30	60	1	1.3955	5	2012	1.7%
12040014	G0362?02.CQC	7	0.362	102	1218670	b/w4	mp	B70250	54	162	1	0.612469	6	2012	0.6%
12050105	C0415?59.TQA	5.5	0.415	59	1228650	W/R5	LM	B80009	51	204	2	1.05	6	2012	1.0%
12050105	C0415?59.TQA	5.5	0.415	59	1228870	B/W3	JT	B80016	45	180	4	2.1	6	2012	2.2%
12050104	C0415?02.CQA	5.5	0.415	102	1227590	W/R6	LM	B80051	45	180	1	0.56	6	2012	0.6%
12050104	C0415?02.CQA	5.5	0.415	102	1227440	W/B4	JM	B80078	45	180	1	0.56	6	2012	0.6%
12050104	C0415?02.CQA	5.5	0.415	102	1227030	BW5	FF	B80091	42	168	2	1.11	6	2012	1.2%
12010002	C0415?02.CQA	5.5	0.415	102X	1202380	R/W2	LM	B80116	41	164	2	1.11	6	2012	1.2%
12030029	C0476W02.CQA	5.5	0.476	102	1212200	B/W4	LM	B80118	42	168	3	1.46	6	2012	1.8%
12060030	I0375I54.HQA	7.625	0.38	54	1231490	W/R5	LM	B80183	36	144	2	1.47	6	2012	1.4%
12150001	G0362?02.HQA	7	0.367	102	884969	R/W5	JM	B81335	91	364	2	1.264505	7	2012	0.5%
12070035	G0317V50.CCA	7	0.317	50L	1237330	r/w6	mp	B80346	48	192	1	0.55349	7	2012	0.5%
12150002	C0415?02.CQA	5.5	0.415	102	889299	w/r2	mp	B81474	135	540	1	0.55437	7	2012	0.2%
12050001	C0415?59.CQA	5.5	0.415	59	1225030	R/W2	JM	B90015	48	192	2	1.05	7	2012	1.0%
12050001	C0415?59.CQA	5.5	0.415	59	1223740	R/W6	LM	B90036	45	180	1	0.525	7	2012	0.6%

Table 3-1: Excel data file with product and reject records

3.3.1 Process Analysis: Mapping the Process (Measure)

Mapping the process is a critical and essential step during the “Measure” phase of DMAIC. The process map is the baseline for process and data analysis. The process map was constructed over several working sessions that were composed of physically walking the process and documenting the process step and the relating input and output variables. The process map in Figure 3-12 summarizes the findings from the working sessions. Each process step has several critical parameters that need to be met in order to produce a good tube. The team also found the recommended operating ranges for each product family in standard operating procedures (SOP's). The output of these sessions presented 12 process steps and 65 potential input variables (X's) inside of the rolling process.

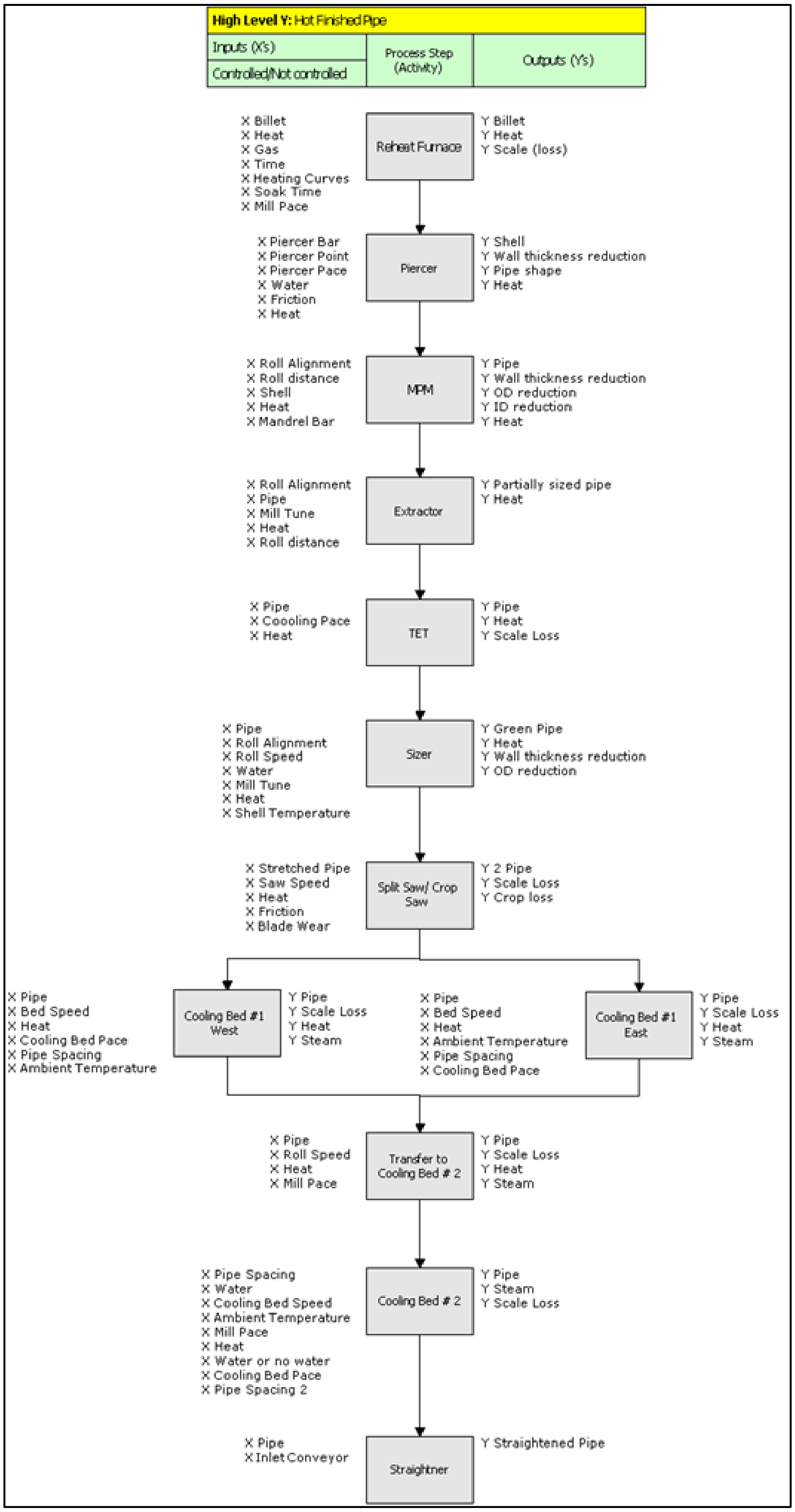


Figure 3-12: MPM process map with input and output variables

The process map presented many potential contributors to bowed pipe rejects. Most of the input variables are quantitative and were able to be analyzed with the tools of Six Sigma.

3.3.2 Process Analysis: Step by Step (Measure)

The next step of the process analysis was to break down each rolling step and to identify which variables could contribute to bowed pipe. As previously mentioned, there are six major steps of the rolling process. The first step of the hot rolling process is the billet reheat furnace. The reheat furnace heats the solid billets from the surface to the core through, this is achieved by moving the billets through three heating zones. The zones include preheating, heating and soaking. Each zone has a pre-set heating program that ensures the billet will be heated uniformly from the OD to the core. Figure 3-13 illustrates the zones inside of the billet reheat furnace. The heating process is essential to rolling a uniform pipe. During reheating, billets are heated to a temperature around 2350° Fahrenheit. The purpose of this step is to make the steel malleable. This helps to ease the stresses introduced during the piercing process and to ensure a more uniform shell after piercing [18]. A heated billet helps to increase the life of the piercing mill tooling and gives a better-quality shell. A more uniform shell needs less forming during the rolling process. A billet that is not heated uniformly is a perceived common cause that leads to a bowed pipe downstream.

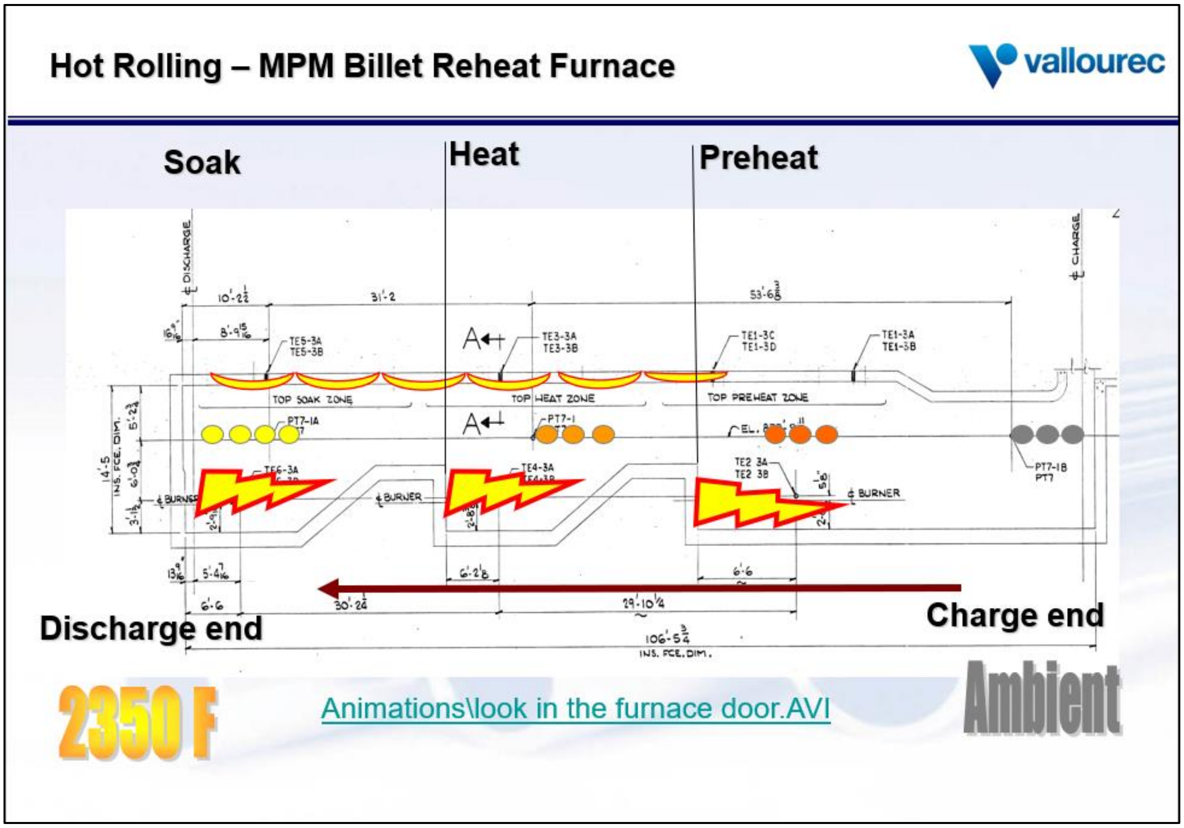


Figure 3-13: MPM Billet Reheat Furnace

The second step of the rolling process is the piercing mill. The primary function of the piercing mill is to pierce a hole in the solid billet. The piercing mill is the first forming step of the rolling process. The piercing mill creates the rough ID profile and wall thickness of the shell [18]. The piercing process is broken down in Figures 3-14, 3-15 and 3-16. The MPM piercing mill utilizes the cross-roll piercing method that utilizes two large rollers to guide the piercing bar to the center of the solid billet. The cross rolls are aided by Diescher disks. Diescher disks are large circular discs that are horizontally aligned to the billet OD to help guide it to the center of the piercing bar. The piercing mill is the most difficult process to analyze due to many of the critical operating factors not being able to be measured while the mill is running. One of the initial hypotheses was, if the wall thickness has too much variation it will cause a pipe to bow.

Figure 3-14: Piercing Mill inside of Vallourec Star's MPM

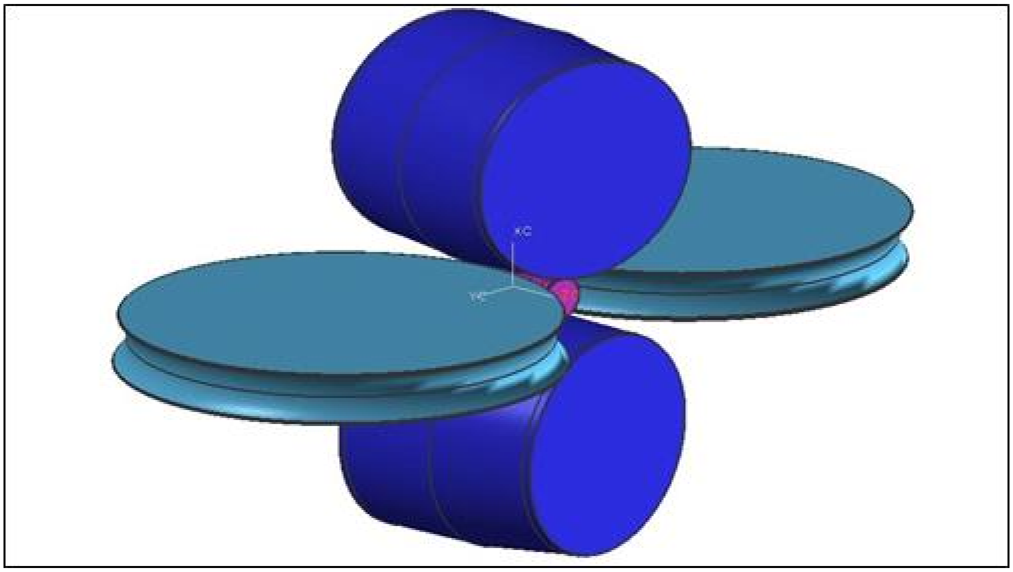


Figure 3-15: Diagram of Diescher disks and cross rolls

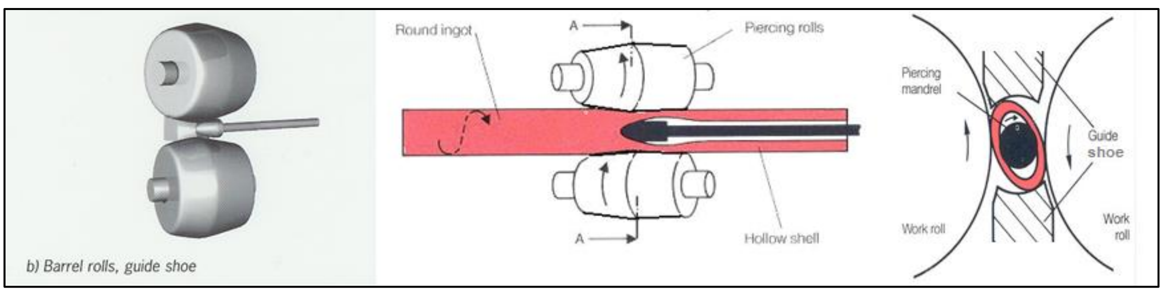


Figure 3-16: Diagram of cross rolls and piercing bar

The third step of the rolling process is the multi-stand pipe mill or MPM. The MPM is where the OD, ID and wall thickness of the hollow shell are formed. The MPM mill utilizes six in-line roller stands, each decreasing in diameter to form the OD of the shell. Figure 3-17 gives a visual of an MPM roll stand. To form the ID a mandrel bar is utilized. A mandrel bar is a hardened solid steel bar machined to a specific OD, shown in Figure 3-18. A mandrel bar is inserted into the shell prior to entering the MPM. The mandrel helps to push the shell through the mill and keeps the pipe from collapsing. This process inside of the MPM is referred to as a retained mandrel process. The mandrel bar stays with the shell through rolling and is then extracted from the shell after the tube exits the roll stands.

Figure 3-17: MPM stand

Figure 3-18: Mandrel bars laying in a rack

The fourth step, which is also the final forming step is the sizing process. The sizing mill elongates the shell and forms the final dimensions of the tube. The sizing mill inside of the MPM consists of a 9 in-line roll stands that decrease in diameter to form the final OD. The OD is reduced up to 25% depending on the product and the sizing mill arrangement.

The fifth step of the rolling process is cooling. The cooling process consists of two phases of cooling. Figures 3-19 and 3-20 show both phases of the cooling process. After the sizing, tubes enter one of two cooling beds where tubes are rotated and air cooled. Each tube is separated into pockets that are balanced to the speed of the mill. The tubes are then transferred to the second cooling station by conveyor where they are air cooled on the first half of the bed and then water cooled over the last half. The tubes are showered with water to bring them down to the ambient temperature. The cooling process is where the bowed pipe issue begins. Once the tubes begin to cool and transition between metallurgical phases, they begin to exhibit this bowing phenomenon.

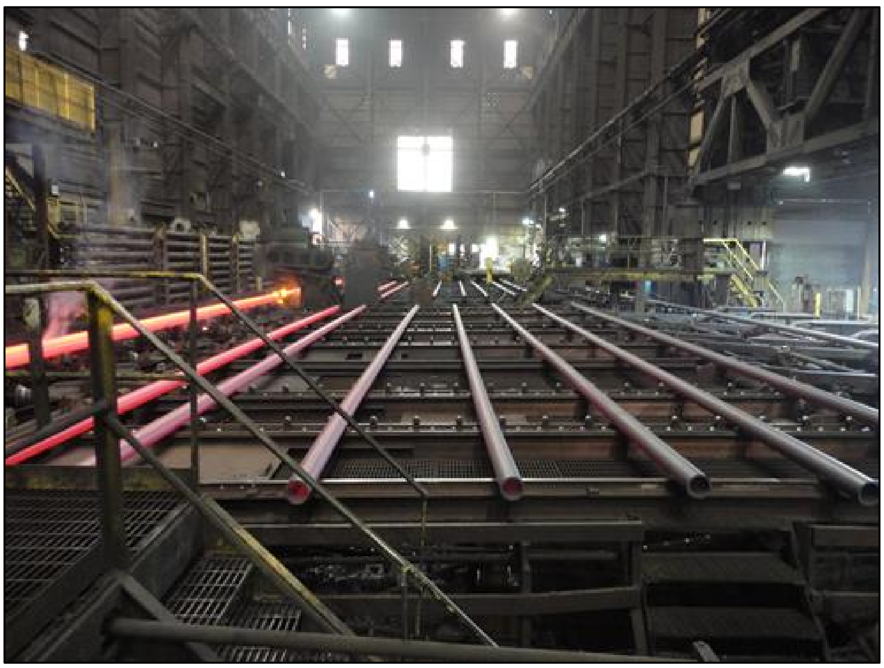


Figure 3-19: The first cooling tables. Cooling Bed #1 & Cooling Bed #2

Figure 3-20: The second cooling station. Highlighting the water-cooling station

The sixth and final process step of the rolling process is the straightening mill. The straightener reduces the amount of bend or slight hook a tube may have in the middle section. The straightener is only able to handle a minimal hook, therefore tubes that are too bowed have to be removed from the process. Tubes are dropped into a conveyor and run through the straightener where they are forced through pressurized roll stands that squeeze the pipe to a desired level of straightness. Figure 3-21 gives a visual of the straightener.

Figure 3-21: Inlet of Straightening Mill

3.4 Determination of Process Variables (Measure)

The knowledge presented from the process analysis led the team to the brainstorming process. The purpose of brainstorming was to classify and then prioritize which process steps and variables were most significant. The tool used to facilitate this activity was the Ishikawa (fish-bone) diagram. The Ishikawa diagram helps to make the link between cause (X) and effect (Y). It also gives the ability to categorize variables by the potential source [10]. Figure 3-21 shows the output of the first round of brainstorming. The sources the team utilized were environment, materials, manpower, methods, equipment and measurement. Each of these potential sources were thought to be the largest categorical contributors to explain the defect. Each main branch represented the team's thoughts on the areas we wanted to analyze further.

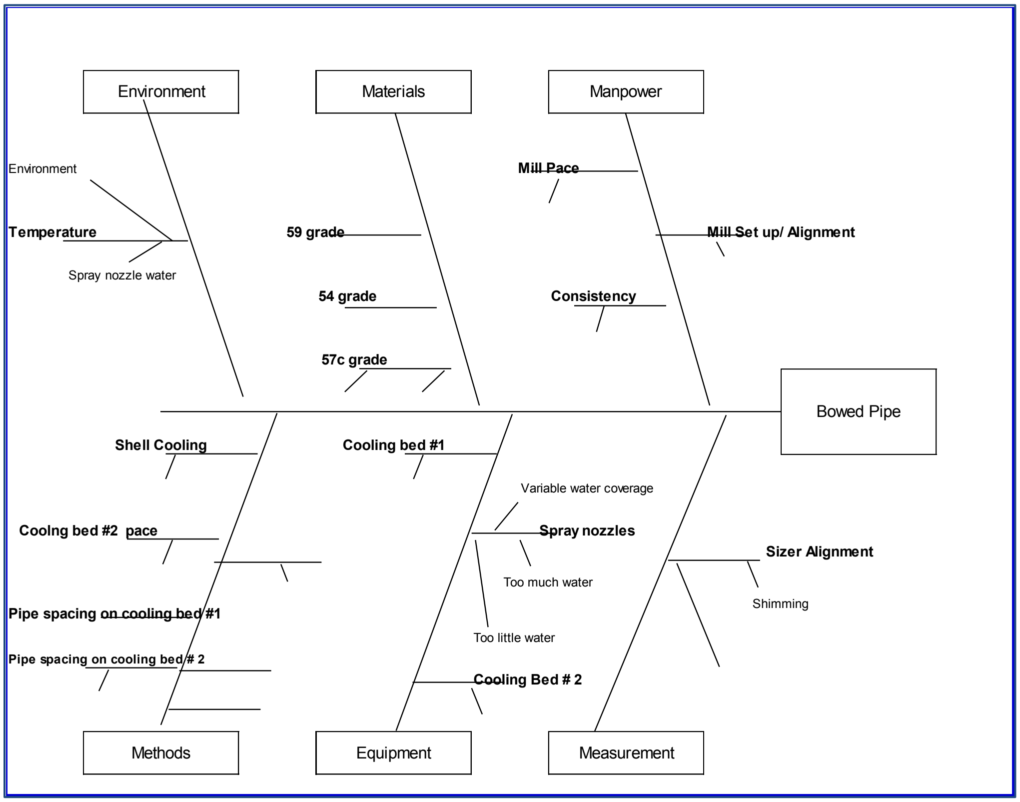


Figure 3-22: Ishikawa Diagram

The Ishikawa exercise helped to raise two questions. “If we do not run the process inside of the optimal ranges at each step, what could go wrong? If something went wrong, how bad would it be?” These questions were important and necessary to narrow our investigation in the next steps. This led the team to the failure modes and effects analysis (FMEA). The FMEA is a brainstorming tool used to anticipate problems, to put actions in place to counteract those problems and to reduce or eliminate risks. The tool allows improvement teams to identify ways in which a change in their process or service could cause unintended problems [10]. The FMEA also helps to form hypotheses to be studied later during the DMAIC process. The FMEA exercise was conducted with the extended team, including the engineers from the Melt Shop. The FMEA process ties each failure mode back to a process step and a set of controlled or uncontrolled variables. Each potential failure mode is given a ranking for its perceived severity to the effect (bowed pipe), the likelihood of its occurrence and the current effectiveness of the detection method(s). Table 3-2 illustrates the details of the ranking system and Table 3-3 shows the results of the FMEA exercise. All three of these indices are multiplied together to give a risk priority number (RPN). The RPN factor gave priority to which factors the team should investigate and which to eliminate from the first round of analysis. The activity brought forward seven potential failure modes.

I. Inconsistent mill pace and cooling bed pace – Pipe being cooled unevenly due to spacing issue on the cooling beds

II. Pipe missing the inlet conveyor to the straightener – Pipe that is too bowed to move naturally through the process. This causes the mill to stop. All in process tubes have to be scrapped.

III. Uneven heating from the billet reheat furnace – The furnace does not rotate if the walking beams are not moving. Any significant delay can cause the billets to be heated unevenly.

IV. Billet chemistry coming from the melt shop – Variation between recommended ranges for alloy additions can cause issues.

V. Sizing mill pass design – Sizing mill rolls could wear prematurely causing changes in shell temperature

VI. Too much water during the second cooling process – Too much water may shock the pipe

VII. Light wall vs. heavy wall situation coming out of the MPM – If the wall thickness of the pipe is not uniform it could cause pipe to bow during the cooling process

RATING	DEGREE OF SEVERITY	LIKELIHOOD OF OCCURRENCE	ABILITY TO DETECT
1	Customer will not notice the adverse effect or it is insignificant	Likelihood of occurrence is remote	Sure that the potential failure will be found or prevented before reaching the next customer
3	Customer is made uncomfortable or their productivity is reduced by the continued degradation of the effect	Relatively moderate failure rate with supporting documentation	Moderate likelihood that the potential failure will reach the next customer
7	Customer endangered due to the adverse effect on safe system performance without warning before failure or violation of governmental regulations	Assured of failure based on previous claim	Absolute certainty that the current controls will not detect the potential failure

Table 3-2: Ranking system for FMEA exercise

Process or Product Name:	Bowed Pipe					Prepared by: Bowed Pipe Team		
Responsible:						FMEA Date (Orig) 8/10/2011 (Rev)		
Process Step/Part Number	**Potential Failure Mode**	**Potential Failure Effects**	**SEV**	**Potential Causes**	**OCC**	**Current Controls**	**DET**	**RPN**
What are the process steps?	In what ways can the process step go wrong?	What is the impact of the Failure Mode on the customer?	How severe is the effect on the customer?	What are the causes of the Failure Mode?	How often does the Cause or Failure Mode occur?	What are the existing controls and procedures that prevent the Cause or Failure Mode?	How well can you detect the Cause or Failure Mode?	Calculated
Inconsistent pace coming from the sizer	Pipe not being consistently spaced causes uneven cooling	Bowed pipe	7	Uneven spacing on cooling bed #1 from sizer	7	No set procedure prior to trials	7	343
Reheat furnace	Uneven heating	Bowed pipe	7	lack of rotation in the furnace, down time between heats	7	There are SOPs in place	7	343
Inlet conveyor	Pipe missing rolls causing pace to stop	Bowed pipe	7	Pipe missing conveyor and having to be manually moved	7	Crane move	3	147
Chemistry	(stirring at furnace, additoins at ladle furnace, or tapping a heat	Scrapped pieces, damages straightener or pipe	7	(stirring at furnace, additoins at ladle furnace, or tapping a heat	3	No measures in place we know of	7	147
Sizing Mill	Shell Temperature	Bowed pipe	7	Pass size in sizing mill, lack of adjustability in operation	3	Roll shop procedures to measure passes	3	63
Water Sprays on cooling bed # 2 (N,S)	Too much or too little water, or no water can cause uneven cooling, pipe shock	Bowed Pipe	3	Uneven cooling, temperature; amount	3	On, off buttons and valves	3	27
MPM	Inconsistent wall profile (light opposing light, or light opposing heavy)	Bowed pipe	3	Roll Chalks (dimensions), mill setup	3	Some but incomplete	3	27

Table 3-3: Output of FMEA exercise

The FMEA exercise helped the team to form hypotheses for potential causes of bowed pipe.

I. Ho: Inconsistent mill pace vs. cooling bed #2 pace causes bowed pipe

II. Ho: Uneven pipe spacing causes bowed pipe

III. Ho: Too much water at CB#2 causes bowed pipe

IV. Ho: Outside air blowing into bay on pipes causes bowed pipe

V. Ho: Variation in alloy additions (Chemistry) at LMF causes bowed pipe

VI. Ho: Down time between heats & lack of rotation in billet furnace contributes to bowed pipe (Over heating of billets)

VII. Ho: Inconsistent shell temperature out of the sizing mill increases probability of bowed pipe

VIII. Ho: Inconsistent sizer mill wear increases the probability of bowed pipe

These eight hypotheses laid out the path for investigation for the next phase of action. Note: Hypotheses I and II are related. The last step of the “Measure” phase was to prioritize which data to look into first. The team chose to use a priority matrix to categorize impacts into critical and non-critical categories. The rating system used set items that receive a rating higher than 150 as critical. This categorization is based on upstream and downstream impact. The methodology is similar to the FMEA, using a force ranking system with numbers 1, 3, 9. 1 = impact is minimal, 3 = variable has a moderate impact, 9 = variable has significant impact. Table 3-4 shows the output of the priority matrix. The critical variables identified from the priority matrix are mill pace, mill tune, product chemistry, BRF heating curves, cooling bed pace, caster speed, pipe spacing and the inlet conveyor condition for the straightening mill.

Prioritization Matrix

Project: Bowed Pipe CIT

Date:

Conclusion: Ho: Any factor with Score >150 are critical

How to fill in the Prioritization Matrix

Importance of each Process Step relative to High Level Y		5	5	5	5	5	5	5	5	5		
	Process Step	Reheat Furnace	Piercer	MPM	Extractor	TET	Sizer	Cooling Bed #1 West	Cooling Bed # 2	Straightner		
Process Map - Activity	**Inputs (X Variable)**										**Score**	**Status**
Process Map - Reheat Furnace	Mill Pace	9	9	9	9	9	9	9	9	9	405	Critical
Process Map - Sizer	Mill Tune	0	0	9	3	3	9	9	9	9	255	Critical
Unmapped Variable	Product Chemistry	9	3	3	1	1	3	9	9	9	235	Critical
Process Map - Reheat Furnace	Heating Curves	9	1	3	1	1	1	9	9	9	215	Critical
Process Map - Cooling Bed # 2	Cooling Bed Pace	0	0	3	1	1	9	9	9	9	205	Critical
Process Map - Cooling Bed #1 West	Cooling Bed Pace	0	0	3	1	1	9	9	9	9	205	Critical
Unmapped Variable	Caster Speed	3	3	3	1	1	1	9	9	9	195	Critical
Process Map - Cooling Bed #1 West	Pipe Spacing	0	0	1	1	1	9	9	9	9	195	Critical
Process Map - Cooling Bed # 2	Pipe Spacing 2	0	0	0	1	1	9	9	9	9	190	Critical
Process Map - Straightner	Inlet Conveyor	0	0	0	0	0	9	9	9	9	180	Critical
Process Map - Reheat Furnace	Soak Time	9	3	3	0	1	1	3	3	3	130	Potential
Process Map - Cooling Bed # 2	Water or no water	0	0	0	1	1	3	1	9	9	120	Potential

Table 3-4: Output of Priority ranking exercise

3.5 Data Analysis Plan

Each hypothesis generated required a specialized approach to prove or disprove. A range of statistical tools and product trials were utilized to better understand how each factor affects bowed pipe. Table 3-5 highlights the desired understanding and analysis tools used for each of the eight hypotheses. For the first hypothesis, Inconsistent mill pace vs. cooling bed #2 pace causes bowed pipe. The desired understanding from this hypothesis was to understand how mill pace and pipe spacing affected bowed pipe. The tools used to analyze if a relationship existed were Pearson correlation, linear regression and graphical analysis. The second hypothesis, uneven pipe spacing on cooling bed # 1 causes bowed pipe. The desired outcome was to understand if the number of pipes on the first set of cooling beds had an effect on bowed pipe. The tools utilized to understand this effect were mill trials and a cooling bed study. The third hypothesis, too much water at CB#2 causes bowed pipe. The desired outcome for this hypothesis was if showering the pipe with too much water had an effect on bowed pipe. The method used to evaluate were mill trials. The fourth hypothesis, outside air blowing through bay doors on cooling pipes causes bowed pipe. The desired understanding from this hypothesis was if outside air blowing on hot pipe caused bowed pipes. The tool used to determine were mill trials. The fifth hypothesis, variation in alloy additions (Chemistry) at LMF causes bowed pipe. The desired understanding was how variation in alloys influenced bowed pipe. The tools utilized were linear regression, multiple regression and scatter plots. The sixth hypothesis, down time between heats and lack of rotation in billet furnace contributes to bowed pipe (over heating of billets). The desired understanding from the analysis was if billets stay in the furnace too long, do they cause bowed pipe. The tools used to analyze this relationship were Pearson correlation and linear regression. The seventh and eighth hypotheses, inconsistent shell temperature and sizer housing wear increases the probability of bowed pipe. The desired understanding with this hypothesis was if the exit temperature at the sizing mill had an effect on bowed pipe. The tools used to determine if a relationship existed were Pearson correlation and linear regression. The findings from the brainstorming and prioritization exercises positioned the team to analyze process variables and determine which contribute most to bowed pipe rejects.

Hypothesis	Desired Understanding	Tools Used
Inconsistent mill pace vs. cooling bed #2 pace causes bowed pipe	If a relationship between mill pace and spacing on cooling bed exists	Pearson correlation, linear regression, graphical analysis
Uneven pipe spacing on cooling bed # 1 causes bowed pipe	If the number of pipe on the cooling bed had an effect on bowed pipe	Mill Trials, cooling study
Too much water at CB#2 causes bowed pipe	If showering the pipe with too much water had an effect on bowed pipe	Mill Trial
Outside air blowing into bay on pipes causes bowed pipe	If outside air blowing on hot pipe had an effect on bowed pipe	Mill Trial
Variation in alloy additions (Chemistry) at LMF causes bowed pipe	If variation in alloys cause bowed pipe	Linear regression, multiple regression, scatter plot
Down time between heats & lack of rotation in billet furnace contributes to bowed pipe (Over heating of billets)	If billets that stay in the furnace too long cause bowed pipe	Pearson correlation, linear regression
Inconsistent shell temperature out of the sizing mill increases probability of bowed pipe	If the exit temperature of a pipe had an effect on bowed pipe	Pearson correlation, linear regression
Inconsistent Sizer housing wear contributes to bowed pipe	If wear in the sizing mill rolls had an effect on bowed pipe	Gauging

Table 3-5: Hypotheses, desired understanding and tools used

Chapter 4 ANAYSIS AND RESULTS

4.1 Analyzing the Variables: Melt Shop Alloys

Using the guidance of the priority matrix the team investigated the product chemistry hypothesis first. If the product chemistry is out of tolerance before entering into the pipe mill, focusing on mill variables would only fix a symptom of the problem and not the root cause. Inside of the melting process alloys are added to a base chemistry giving the desired grade specific mechanical properties. Each product has an acceptable range for each alloy. The hypothesis questioned if products were processed out of range, could they contribute to bowed pipe rejects. The team utilized the help of the melt shop process engineers to better understand the process conducted at the ladle metallurgy furnace (LMF). The LMF is where the additions are added to a batch of steel. The LMF also stirs the steel to better mix in these alloys and takes samples to ensure each heat of steel does indeed meet the product specifications. The data recommended to analyze was, the range of alloys added to heats for manganese (MN), silicon (SI), chromium (CR), molybdenum (MO). These four alloys are what give corrosion resistant products their properties.

Several analyses were performed using Pearson correlation, linear regression and multiple regression to determine if any of these factors had an effect on bowed pipe. Each grade and alloy were analyzed individually to ensure validity of the data. The results of the Pearson correlation study gave three key insights into our data. Firstly, if a linear relationship between each alloy and the number of rejects has a relationship.

Secondly, if a linear relationship exists between each alloy and lastly, if any of the correlation coefficients are significant. Figure 4-1 shows results for grade 54. A moderate positive linear relationship exists between manganese and chromium and the correlation coefficient is significant. In other words, if the addition ratio of manganese increases so does the ratio for chromium. All other factors and their relationships to the amount of bowed pipe rejects are insignificant. The key take-away with grade 54 is the variation of manganese and chromium additions tend to trend in the same direction

```
Correlations: MN, SI, CR, MO, Ratio 54 Grade

             MN       SI       CR       MO
SI       -0.019
          0.895

CR        0.538   -0.368
          0.000    0.007

MO        0.261   -0.153    0.202
          0.061    0.279    0.151

Ratio     0.090    0.067    0.013    0.119
          0.528    0.636    0.930    0.399


Cell Contents: Pearson correlation
               P-Value
```

Figure 4-1: Pearson correlation results for grade 54

Note: Significant results are highlighted in yellow

Figure 4-2 shows the results of the Pearson correlation study for grade 57C. No linear relationships exist between the alloys, none have an impact to bowed pipe and none of the correlation coefficients are significant. The Pearson study helped us to conclude alloy variation has no effect on bowed pipe for grade 57C.

```
Correlations: MN_2, SI_2, CR_2, MO_2, Ratio_2 Grade 57C

             MN_2     SI_2     CR_2     MO_2
SI_2        0.221
            0.050

CR_2        0.108    0.161
            0.342    0.155

MO_2        0.007   -0.199   -0.063
            0.953    0.079    0.583

Ratio_2     0.054    0.167    0.174    0.145
            0.638    0.140    0.125    0.203


Cell Contents: Pearson correlation
               P-Value
```

Figure 4-2: Pearson Correlation results for grade 57C

Figure 4-3 shows the Pearson study results for grade 59. Grade 59 was the most interesting grade to study due to the majority of bowed pipe rejects occurring with this grade. The results from the Pearson study highlighted the correlation coefficient was significant for the relationship between silicon and bowed pipe rejects. The main take away from these results were to run a linear regression study in order to see how strong the R^2 factor was. Figure 4-4 shows the results from the linear regression study. The linear regression validated that a positive relationship exists but the linear regression also gave insight into how much variation was explained in the model. Even through there is a positive relationship between silicon and bowed pipe rejects only 4.62% of the data was explained by the model. This is easy to visualize in the scatter plot. The regression model told us there are other factors that are contributing to our reject.

Correlations: MN_1, SI_1, CR_1, MO_1, Ratio_1 59 Grade

	MN_1	SI_1	CR_1	MO_1
SI_1	-0.084			
	0.539			
CR_1	0.094	0.174		
	0.491	0.200		
MO_1	0.079	-0.063	0.346	
	0.562	0.646	0.009	
Ratio_1	-0.183	0.337	-0.108	-0.189
	0.177	0.011	0.430	0.162

Cell Contents: Pearson correlation
P-Value

Figure 4-3: Pearson Correlation results for grade 59

Note: highlighted area shows the significant correlation coefficient

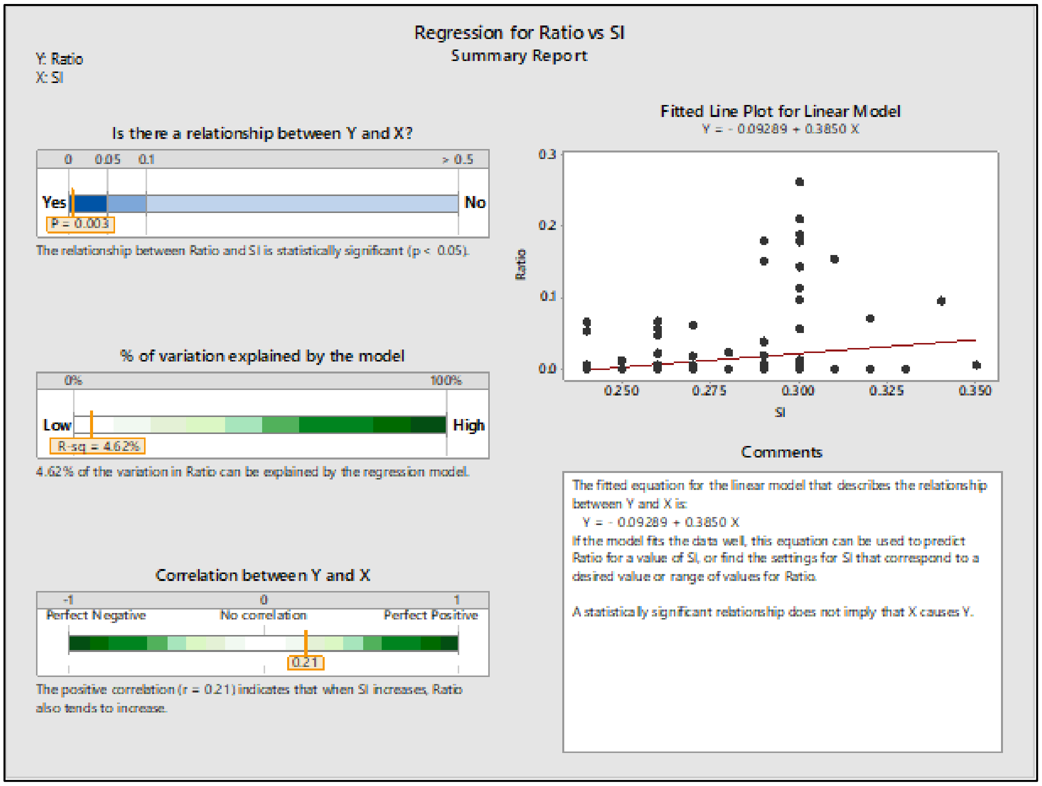


Figure 4-4: Linear Regression results for silicon and bowed pipe

Multiple regression was used to prove or disprove all three alloys together or in combination have an effect on bowed pipe rejects. Figures 4-5 and 4-6 summarize the results. The multiple regression study revealed similar results to the linear regression model. There is a relationship between bowed pipe and these alloys but a significant amount of the data is not accounted for inside of the model. Only 4.62% of the variation in the defect data can be explained with this model. The model also highlighted that manganese, chromium and molybdenum were not significant in explaining variation in the model. The only significant variable was silicon; hence the results were identical to the linear regression study. The scatter plot showed results were better closer to both the lower and upper control limits.

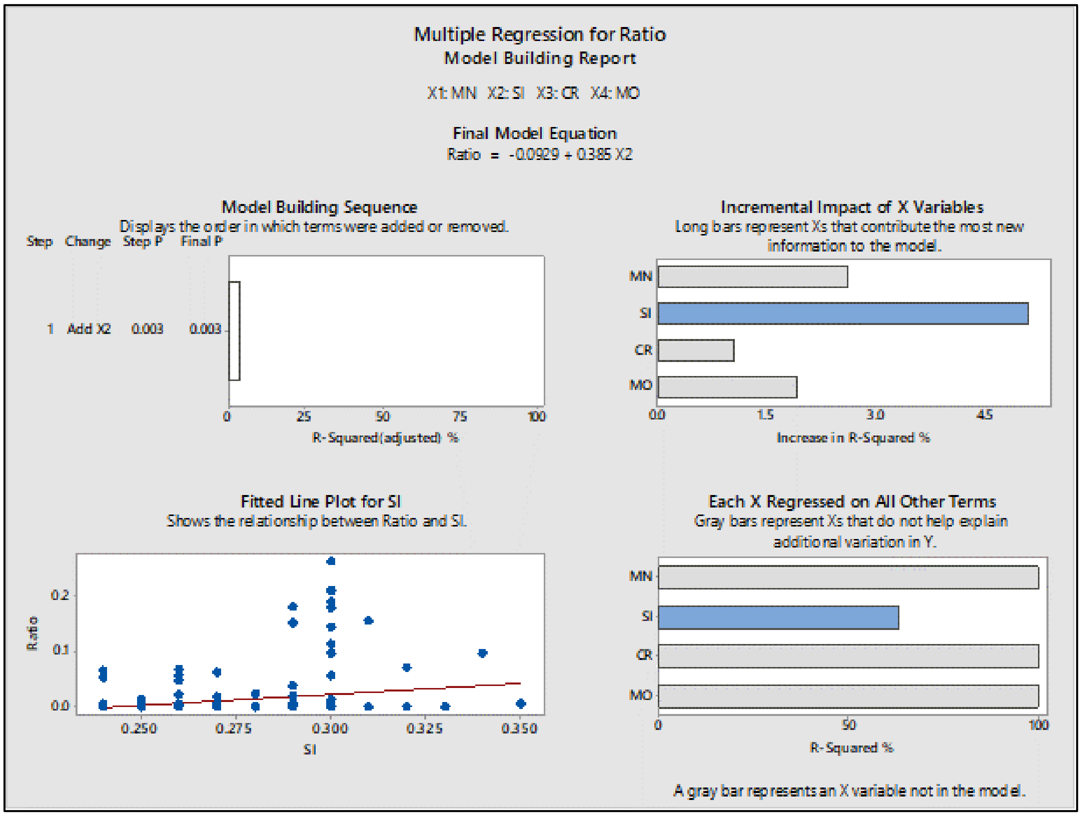


Figure 4-5: Multiple regression results from manganese, silicon, chromium and molybdenum study

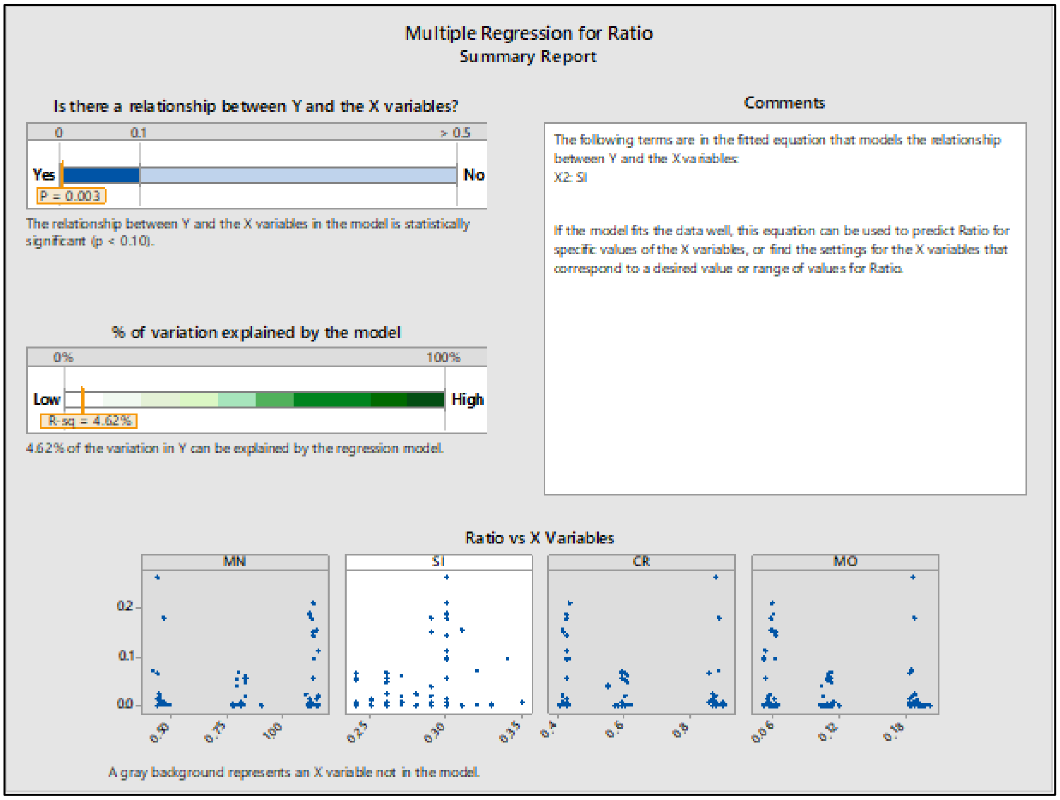
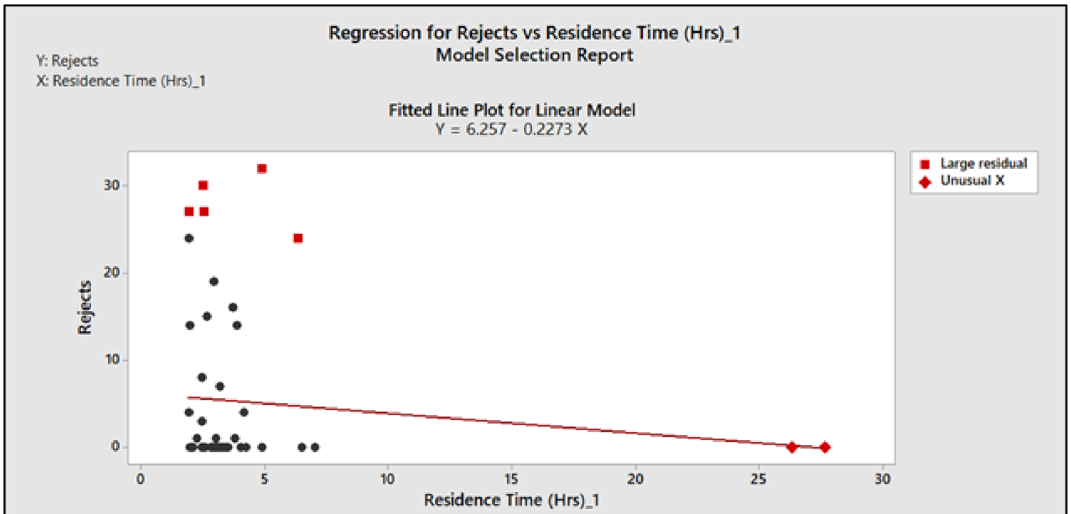


Figure 4-6: Multiple regression results from manganese, silicon, chromium and molybdenum study

Based on the regression studies we concluded that the four alloys together are not the primary cause of bowed pipe rejects. The results also helped us to conclude that silicon does have a relationship with bowed pipes but the model has a significant amount of unexplained variation. The control parameters were added to the list of potential implementation ideas.

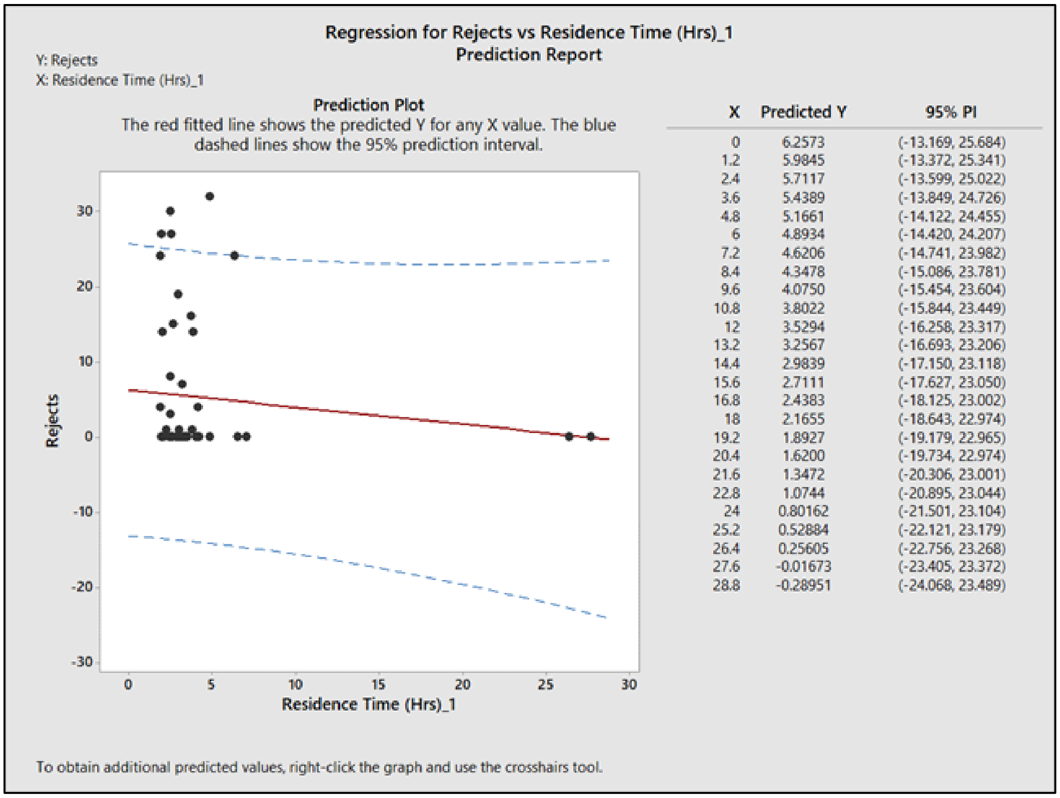
4.2 Analyzing the Variables: BRF Furnace

The next hypothesis explored was the effect of billet reheat time on bowed pipe. This hypothesis was chosen as a result of the prioritization process and it is the first process step in the rolling mill. Linear regression was the tool chosen to explore if a relationship existed. Figures 4-7, 4-8, 4-9, 4-10 show the results of this study.



Statistics	Selected Model Linear	Alternative Model Quadratic
R-squared (adjusted)	0.00%	0.00%
P-value, model	0.422	0.727
P-value, linear term	0.422	0.871
P-value, quadratic term	—	0.977
Residual standard deviation	9.504	9.602

Figure 4-7: Fitted line plot for residence time vs. bowed pipe defects



X	Predicted Y	95% PI
0	6.2573	(-13.169, 25.684)
1.2	5.9845	(-13.372, 25.341)
2.4	5.7117	(-13.599, 25.022)
3.6	5.4389	(-13.849, 24.726)
4.8	5.1661	(-14.122, 24.455)
6	4.8934	(-14.420, 24.207)
7.2	4.6206	(-14.741, 23.982)
8.4	4.3478	(-15.086, 23.781)
9.6	4.0750	(-15.454, 23.604)
10.8	3.8022	(-15.844, 23.449)
12	3.5294	(-16.258, 23.317)
13.2	3.2567	(-16.693, 23.206)
14.4	2.9839	(-17.150, 23.118)
15.6	2.7111	(-17.627, 23.050)
16.8	2.4383	(-18.125, 23.002)
18	2.1655	(-18.643, 22.974)
19.2	1.8927	(-19.179, 22.965)
20.4	1.6200	(-19.734, 22.974)
21.6	1.3472	(-20.306, 23.001)
22.8	1.0744	(-20.895, 23.044)
24	0.80162	(-21.501, 23.104)
25.2	0.52884	(-22.121, 23.179)
26.4	0.25605	(-22.756, 23.268)
27.6	-0.01673	(-23.405, 23.372)
28.8	-0.28951	(-24.068, 23.489)

Figure 4-8: Prediction plot for residence time vs. bowed pipe defects

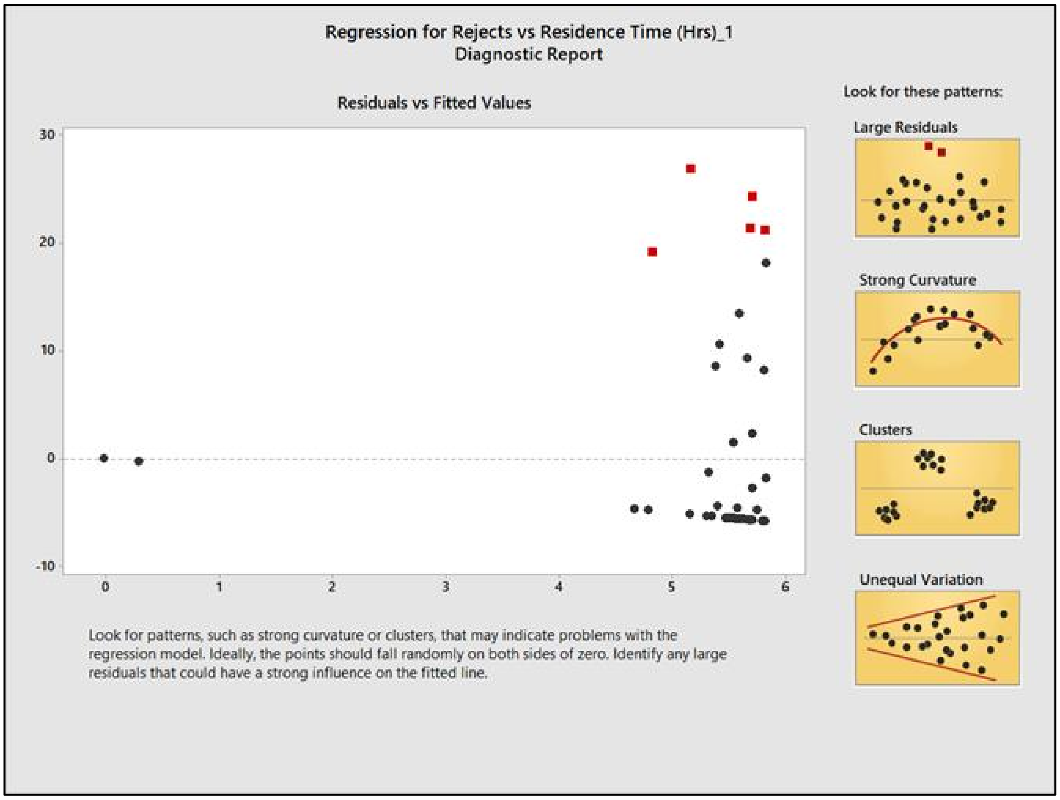


Figure 4-9: Residual plot for residence time vs. bowed pipe rejects

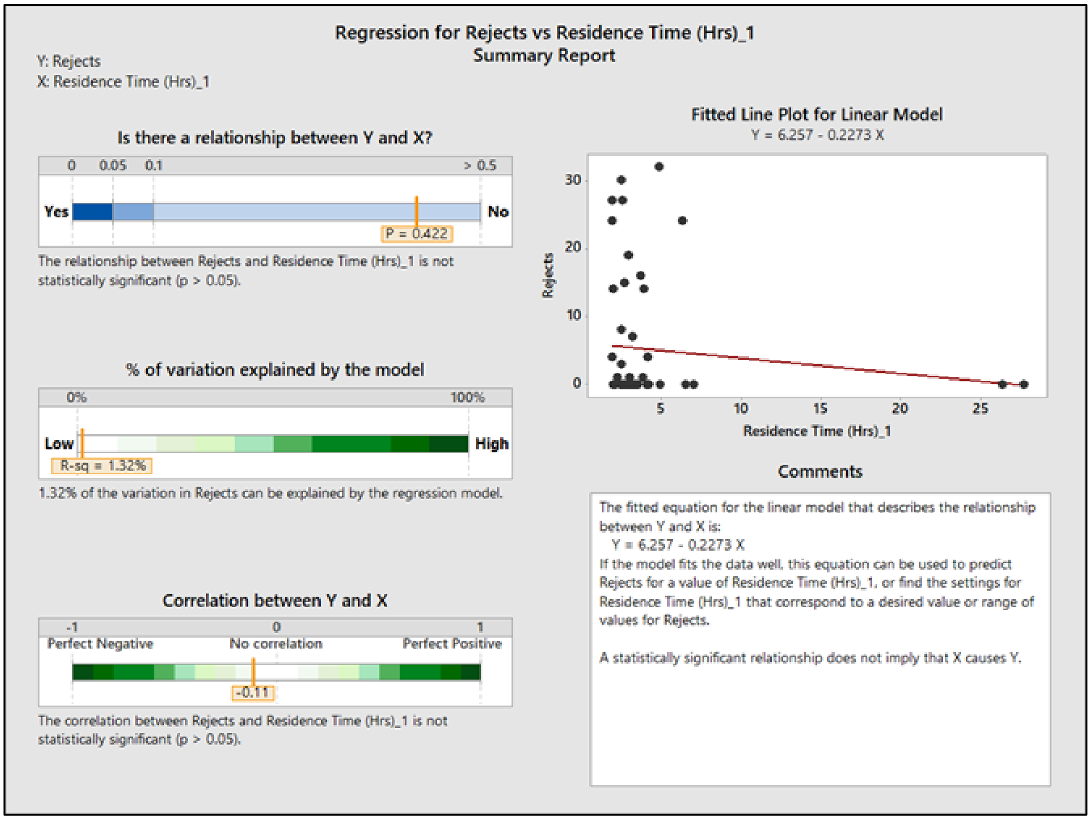


Figure 4-10: Summary report for residence time study

The results reveal there is no relationship between the residence time and bowed pipe rejects. The P value of .422 validates this result. The model was also not strong due to an R^2 value of 1.32%. These results were conclusive enough for the team to reject the null hypothesis and move on to the next hypothesis.

4.3 Analyzing the Variables: Outside Air

Outside air blowing onto cooling pipes was suspected to influence bowing during the cooling process. Analysis was performed using a categorical regression study. The results are presented below in figure 4-11. There is a relationship between the doors being open and bowed pipes. This is supported by the P-value of .046. Oppositely, the R^2

value is .61%, which is very low. A significant amount of variation is not explained in the model. The input from the team was the different mill parameters could explain some of this variation. Ambient wind gusts during the fall, winter or spring months in Ohio could be enough to cool pipe down unevenly. The recommendation from the team was to run with the bay doors closed going forward. This recommendation was added to the list of potential solutions.

Regression Analysis: Rejects versus Bay Door

Method

Categorical predictor coding (1, 0)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	20.56	20.559	4.00	0.046
Bay Door	1	20.56	20.559	4.00	0.046
Error	651	3342.42	5.134		
Total	652	3362.98			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
2.26590	0.61%	0.46%	0.00%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.235	0.117	2.01	0.045	
Bay Door					
Open	0.359	0.179	2.00	0.046	1.00

Regression Equation

Rejects = 0.235 + 0.0 Bay Door_Closed + 0.359 Bay Door_Open

Fits and Diagnostics for Unusual Observations

Obs	Rejects	Fit	Resid	Std Resid	
220	12.000	0.594	11.406	5.04	R
221	9.000	0.594	8.406	3.72	R
222	6.000	0.594	5.406	2.39	R
226	10.000	0.594	9.406	4.16	R
230	6.000	0.594	5.406	2.39	R
233	30.000	0.594	29.406	13.00	R
298	12.000	0.235	11.765	5.20	R
299	22.000	0.235	21.765	9.62	R
302	8.000	0.235	7.765	3.43	R
303	11.000	0.235	10.765	4.76	R
304	12.000	0.235	11.765	5.20	R
305	6.000	0.235	5.765	2.55	R
308	12.000	0.235	11.765	5.20	R
314	10.000	0.594	9.406	4.16	R
417	14.000	0.594	13.406	5.93	R
423	8.000	0.594	7.406	3.27	R
424	19.000	0.594	18.406	8.14	R
425	14.000	0.594	13.406	5.93	R
426	7.000	0.594	6.406	2.83	R

R Large residual

Residual Plots for Rejects

Figure 4-11: Results of categorical regression for bay doors vs. bowed pipe

4.4 Analyzing the Variables: Mill parameters

After determining that no upstream process step had a significant effect on bowed pipe rejects the team decided to study if a relationship exists between the various mill parameters and bowed pipe. There are severable inputs that control the speed of the mill and the rate of cooling. The mill pace, cooling bed #1 speed, cooling bed #1 open pocket speed, cooling bed #1 outlet speed and cooling bed #2 speed. Each of these parameters operate individually and are controlled by different mill operators. This context was important for analyzing the mill data. Regression analysis was used to analyze the mill data and to determine if relationships existed. Figures 4-12 shows the results of the Pearson correlation study. The Pearson study highlighted several important relationships between mill parameters. A moderate correlation exists between the cooling bed # 1 open pocket speed and the speed of cooling bed # 2. This is supported by the .447 correlation value. The results also show several parameters have significant correlation coefficients, highlighted in figure 4-12.

Correlation: Avg CB2 Speed, Avg CB1 Open Pocket, Avg ... ace, Rejects

Correlations

	Avg CB2 Speed	Avg CB1 Open Poc	Avg CB1 Speed	Avg CB1 Outlet S
Avg CB1 Open Poc	0.447			
	0.000			
Avg CB1 Speed	0.330	-0.025		
	0.000	0.465		
Avg CB1 Outlet S	0.201	-0.114	0.318	
	0.000	0.001	0.000	
Mill Pace	0.170	0.279	-0.183	-0.530
	0.000	0.000	0.000	0.000
Rejects	0.091	-0.050	0.175	0.094
	0.007	0.146	0.000	0.006

	Mill Pace
Rejects	0.033
	0.340

Cell Contents
Pearson correlation
P-Value

Figure 4-12: Pearson Correlation results of mill parameters

The Pearson study gave the team good insight and led us to further study these relationships. As mentioned earlier each parameter is controlled by a different operator. This key point validates that each operator could run their part of the process at a different pace than upstream or downstream processes, which presented additional variation. Scatter plots were used to visualize the variation for each mill parameter. Figure 4-13 shows the spread of variation for each.

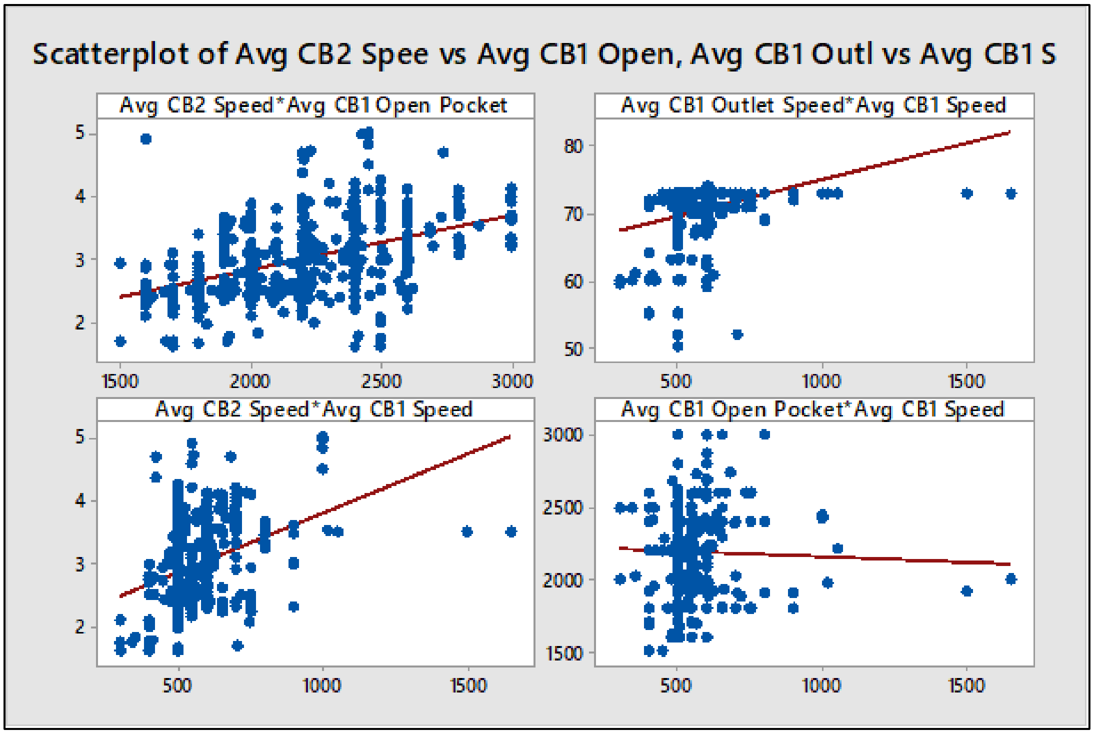


Figure 4-13: Scatter plot for mill parameters

The scatter plots were used as a communication tool for the team members to accompany the Pearson correlation results. The fit lines on the scatter plots show a positive or negative relationship and how closely the residuals fall on that line. For the cooling bed # 2 speed vs. the cooling bed # 1 open pocket speed the residuals are randomly spread above and below the fit line which supports the results from the Pearson study. For each of the other interactions. Cooling bed # 1 outlet speed vs. the cooling bed # 1 speed, the cooling bed # 2 speed vs. the cooling bed # 1 speed and the cooling bed # 1 open pocket speed vs. the cooling bed # 1 speed the residuals are grouped in clusters. These groups signify there were patterns in our data. These patterns mean these parameters had a positive or negative impact on the defect when combined in a certain range with another parameter. Multiple regression was used to further identify which parameters in combination were most significant. Figures 4-14, 4-15, 4-16, 4-17 show the results of the multiple regression study.

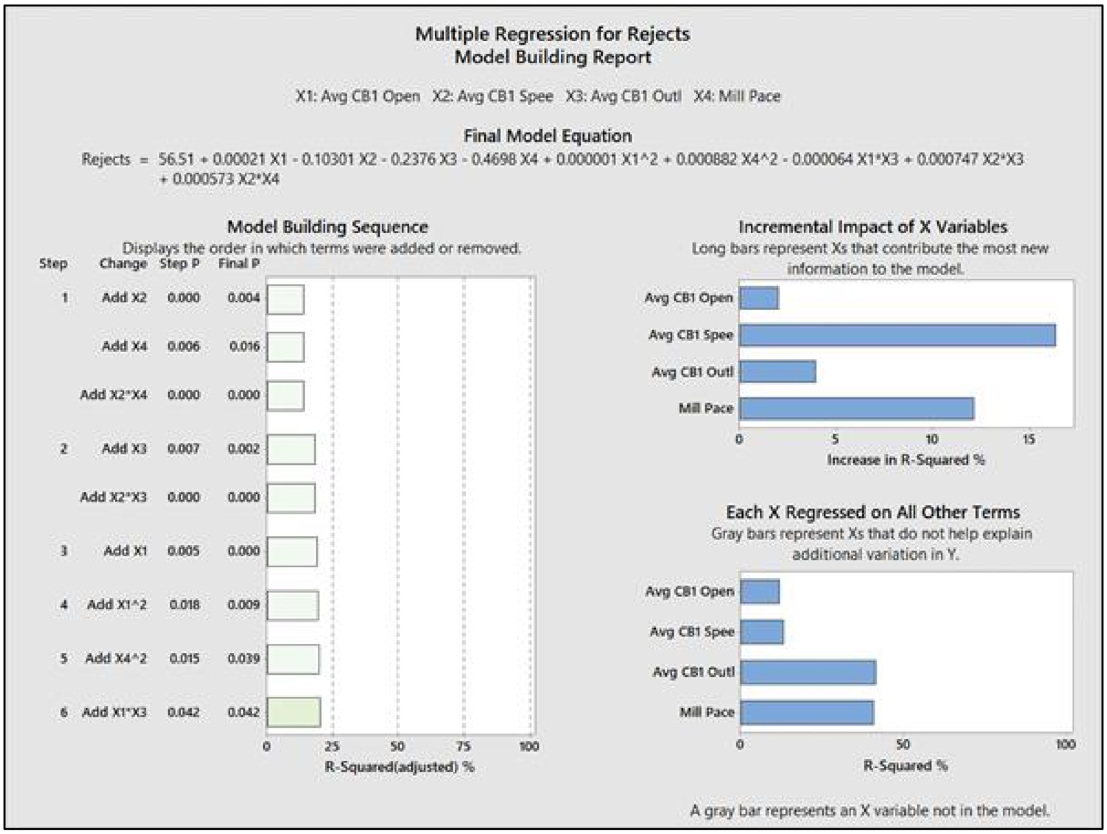


Figure 4-14: Multiple regression model for mill parameters

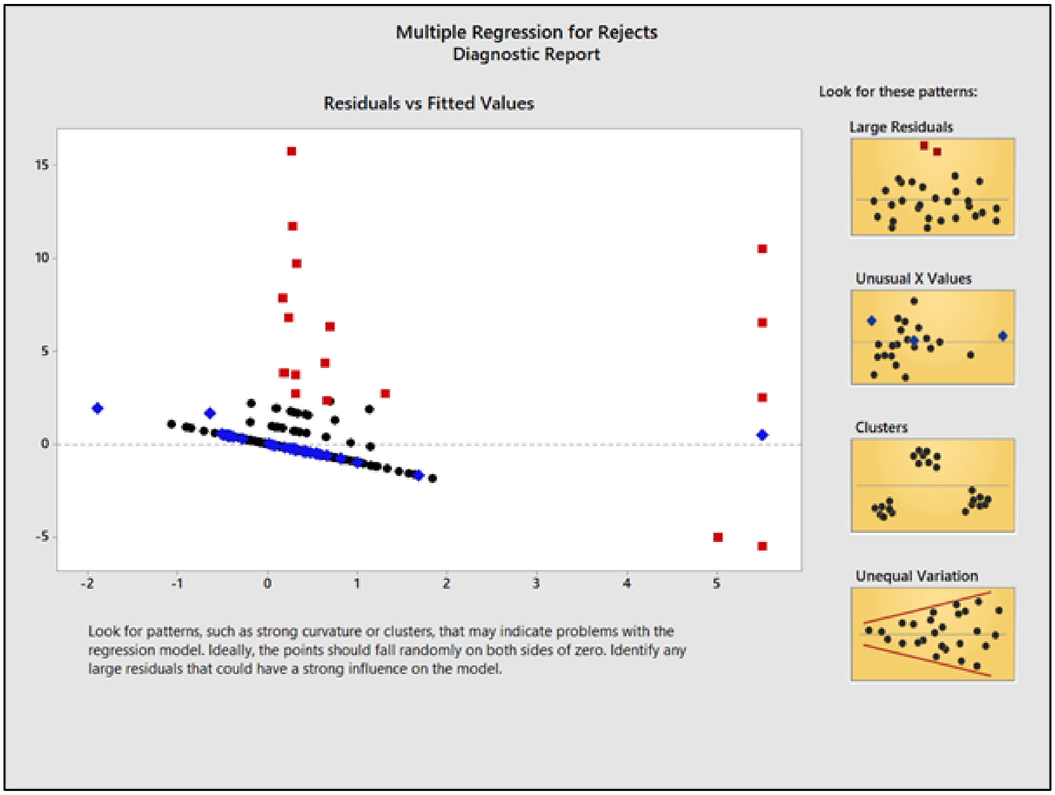


Figure 4-15: Residual plot for mill parameters

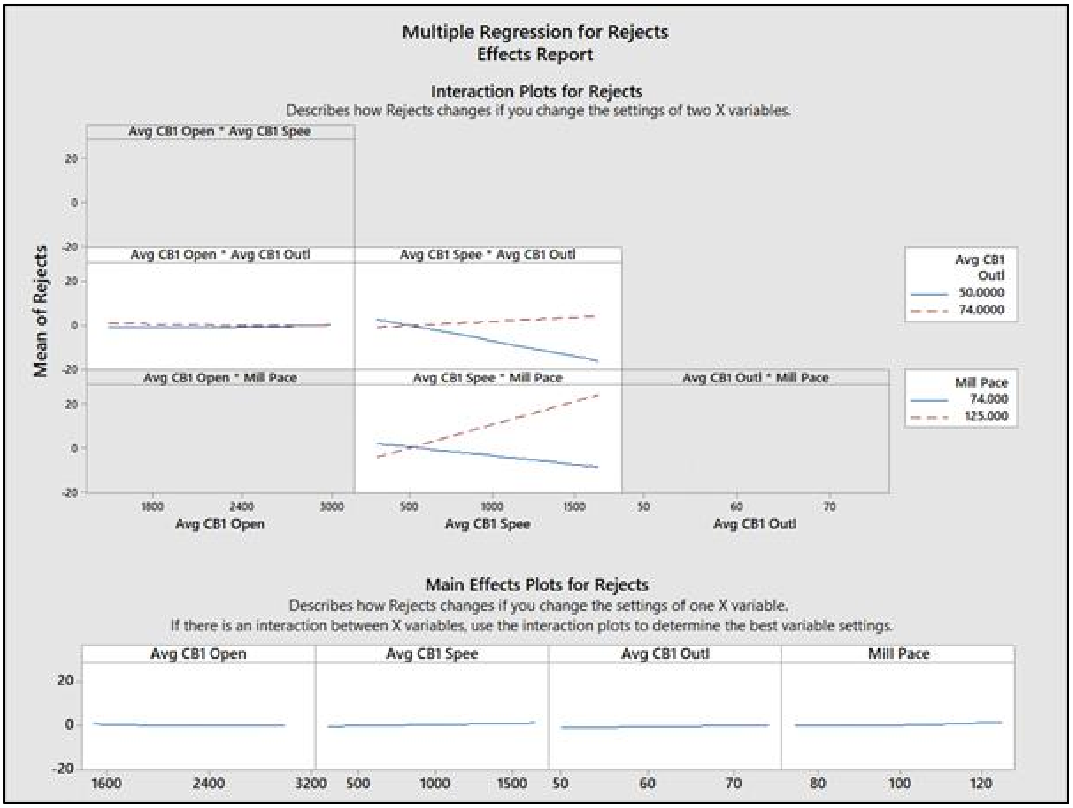


Figure 4-16: Effects report for mill parameters

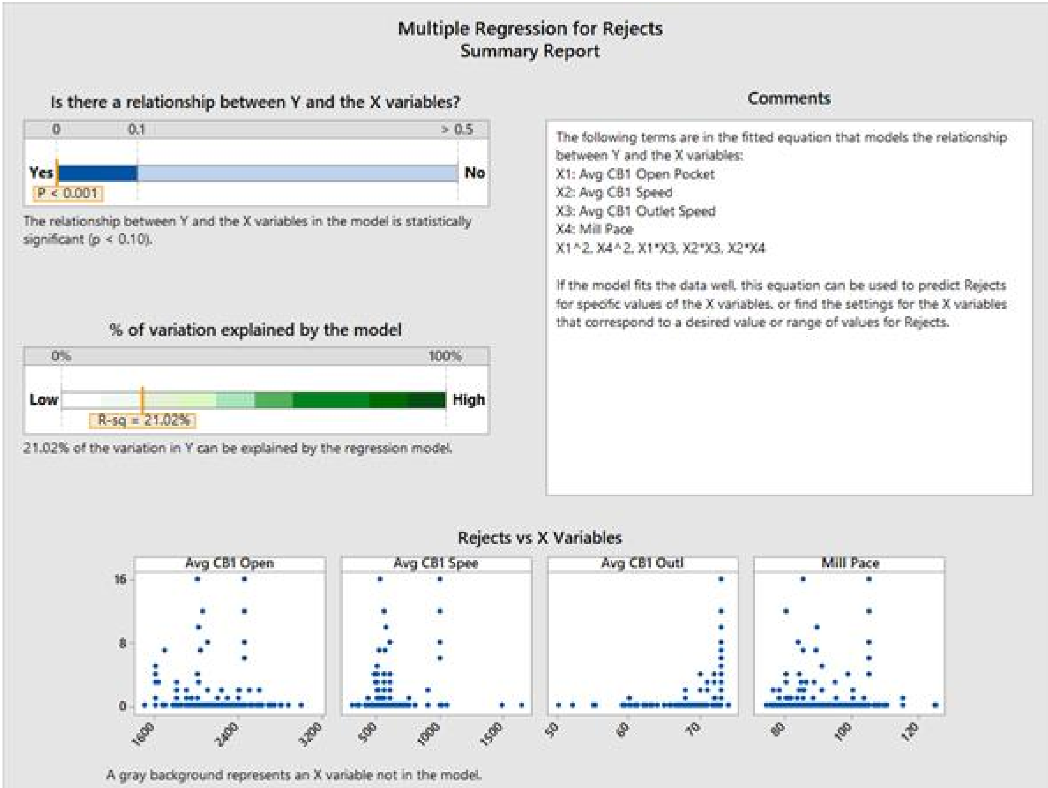


Figure 4-17: Summary report for mill parameters

The multiple regression study supported the null hypothesis of the team. The P value of the study was .001 which supports that a relationship does exist. On the contrary, a significant amount of variation could not be explained in the model, only 21.02% was accounted for.

The study brought forth a method to measure the interactions discovered with the scatter plots. At a faster mill speed in combination with a higher cooling bed # 1 speed defects tend to trend upward. At a low set point for the cooling bed # 1 outlet speed in combination with a faster cooling bed # 1 speed defects tend to go down. Adjusting these parameters produced various scenarios during the cooling process. An observation noted by the team was, the number of pipes on cooling bed # 1 and cooling bed # 2 varied significantly depending on the set points of the mill parameters. The amount and severity of bow also varied greatly with the number of pipes on the cooling bed. The number of pipes and spacing during the cooling process could be a predictor if we will have bowed pipes. Controlling the number of pipes on the cooling beds was added to the potential solutions list.

4.5 Improve: Potential Solutions

Five of the null hypotheses were analyzed and studied. Out of the five, four were proven to be viable and one was disproved. The four that were proven to be viable were promoted to the list of potential solutions. Table 4-1 shows this progression.

No	Hypothesis	Desired Understanding	Tools Used	Studied?	Status
1	Inconsistent mill pace vs. cooling bed #2 pace causes bowed pipe	If a relationship between mill pace and spacing on cooling bed exists	Pearson correlation, linear regression, graphical analysis	Yes	Promoted
2	Uneven pipe spacing on cooling bed # 1 causes bowed pipe	If the number of pipe on the cooling bed had an effect on bowed pipe	Mill Trials, cooling study	Yes	Promoted
3	Too much water at CB#2 causes bowed pipe	If showering the pipe with too much water had an effect on bowed pipe	Mill Trial	No	TBD
4	Outside air blowing into bay on pipes causes bowed pipe	If outside air blowing on hot pipe had an effect on bowed pipe	Mill Trial	Yes	Promoted
5	Variation in alloy additions (Chemistry) at LMF causes bowed pipe	If variation in alloys cause bowed pipe	Linear regression, multiple regression, scatter plot	Yes	Promoted
6	Down time between heats & lack of rotation in billet furnace contributes to bowed pipe (Over heating of billets)	If billets that stay in the furnace too long cause bowed pipe	Pearson correlation, linear regression	Yes	Disproved
7	Inconsistent shell temperature out of the sizing mill increases probability of bowed pipe	If the exit temperature of a pipe had an effect on bowed pipe	Pearson correlation, linear regression	No	TBD
8	Inconsistent Sizer housing wear contributes to bowed pipe	If wear in the sizing mill rolls had an effect on bowed pipe	Gauging	No	TBD

Table 4-1: Hypotheses with status of analysis

Three potential solutions were chosen by the team to trial. First, controlling the number of pipes on the cooling bed. Second, keeping the bay doors closed when rolling high alloy products. Third, to run silicon close to the minimum or maximum control limits during the melting process. These results are shown below in Table 4-2.

No	Potential Solution	Votes	Method
1	Control the number of pipe on the cooling bed	13	Mill trials
2	Keep bay doors closed when running high alloy products	13	Just Do it (JDI)
3	Run silicon closer to lower or upper control limits. Do not run to the "aim" value	10	Trial with Melt Shop

Table 4-2: List of potential solutions for solving bowed pipe

4.6 Improve: Try-storming

Mill trials were coordinated with the focus to keep the same number of pipes on the cooling beds through several campaigns and to chart the results. The study was conducted with all bay doors closed. The team chose to utilize infrared technology to measure the temperature of the pipes during various phases of the cooling process. This gave insight into if the pipe was being cooled uniformly at the various stages. Figure 4-18 shows an infrared picture from the cooling trial. The results of the trial helped us to conclude that insulating the pipe close to each other gave the best result. The closer the pipe were together to one another the more uniformly they cooled. During the trial the team conducted time studies and combined them with the temperatures in various locations in order to get a rate of cooling. This rate of cooling gave us a baseline of how fast we should target to run the mill and cooling beds.

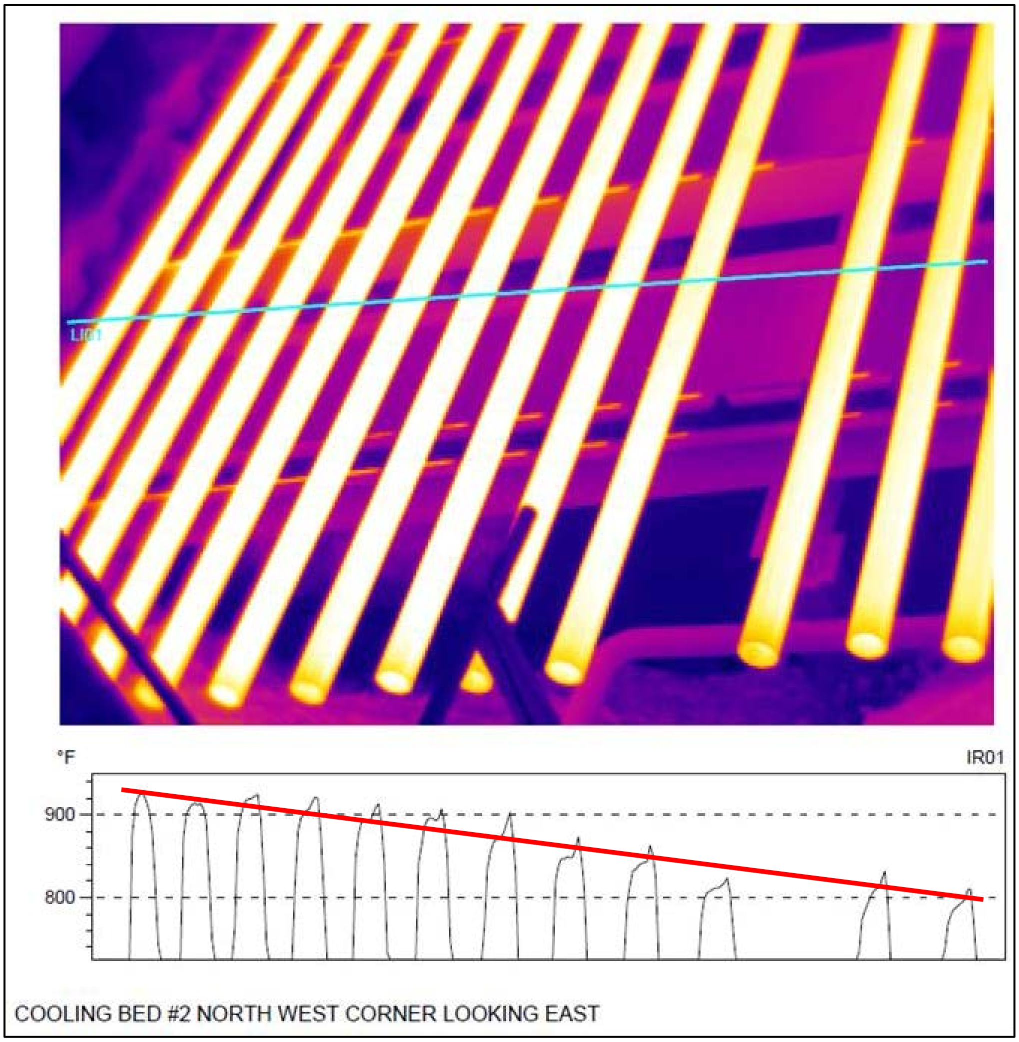


Figure 4-18: Result of cooling trial

Figure 4-19 shows the shell temperatures of each subgroup that was sampled during the trial. The measurements were taken at three points of each pipe. On each end and in the middle. With this data we were able to get a temperature range for each tube. This range told us how much warmer or cooler the ends of the tubes were from the middle with the insulation strategy. When comparing the three temperatures on one tube the smallest deviation was 4 degrees and the largest was 24. This is shown below in figure 4-19.

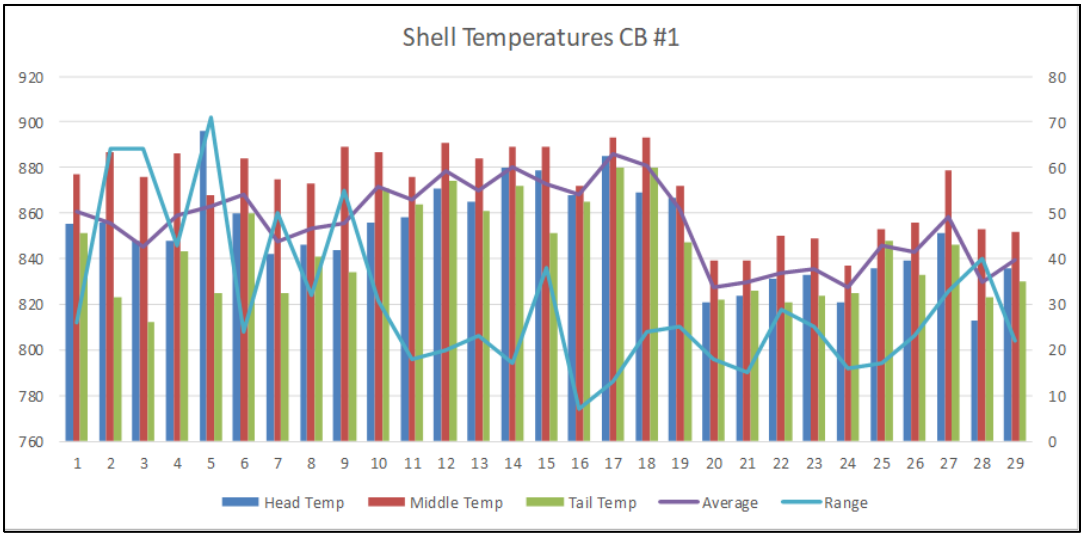


Figure 4-19: Temperature result of cooling trial

The result of the cooling trial was 0 bowed pipe. This gave the team a high level of confidence that controlling the amount of pipe on the cooling bed would have a positive influence on reducing bowed pipe defects. Mill parameters were compared between two periods. Prior to the cooling trial and after. The results of the comparison are shown in figures 4-20 and 4-21. The histograms highlight when the operators focused on controlling the number of pipes of the cooling bed the mill parameters were better controlled. The operating range for each parameter was tighter and the standard deviation was lower. This analysis validated that the mill parameters are significant but controlling the cooling process is most significant when trying to minimize bowed pipe rejects.

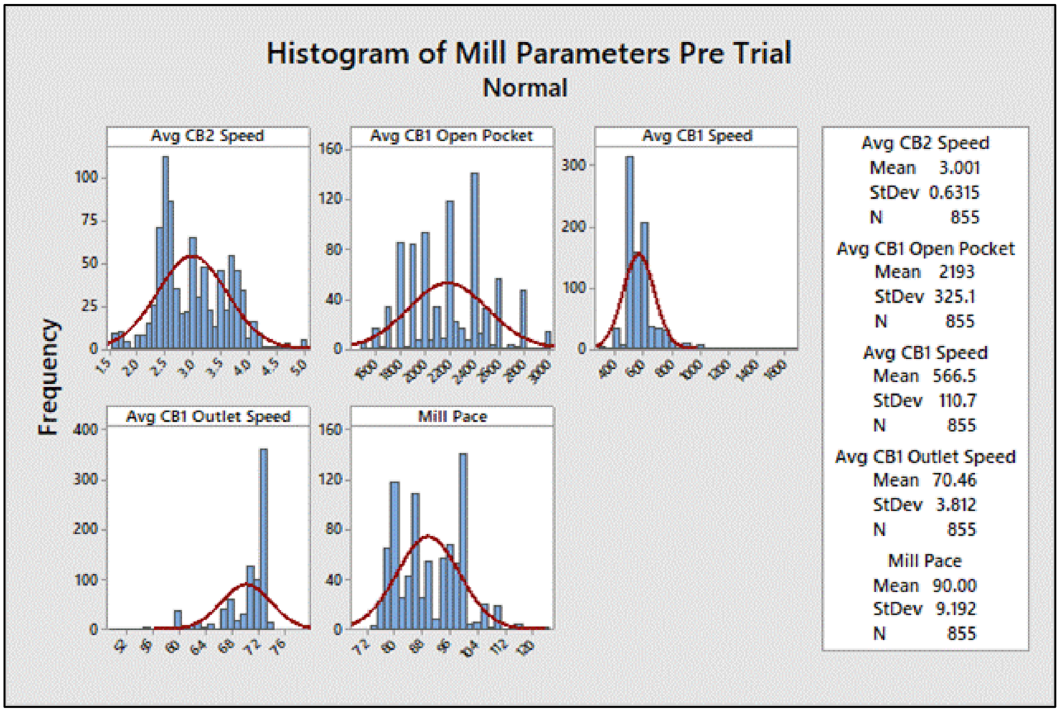


Figure 4-20: Histogram of mill parameters prior to the cooling trial

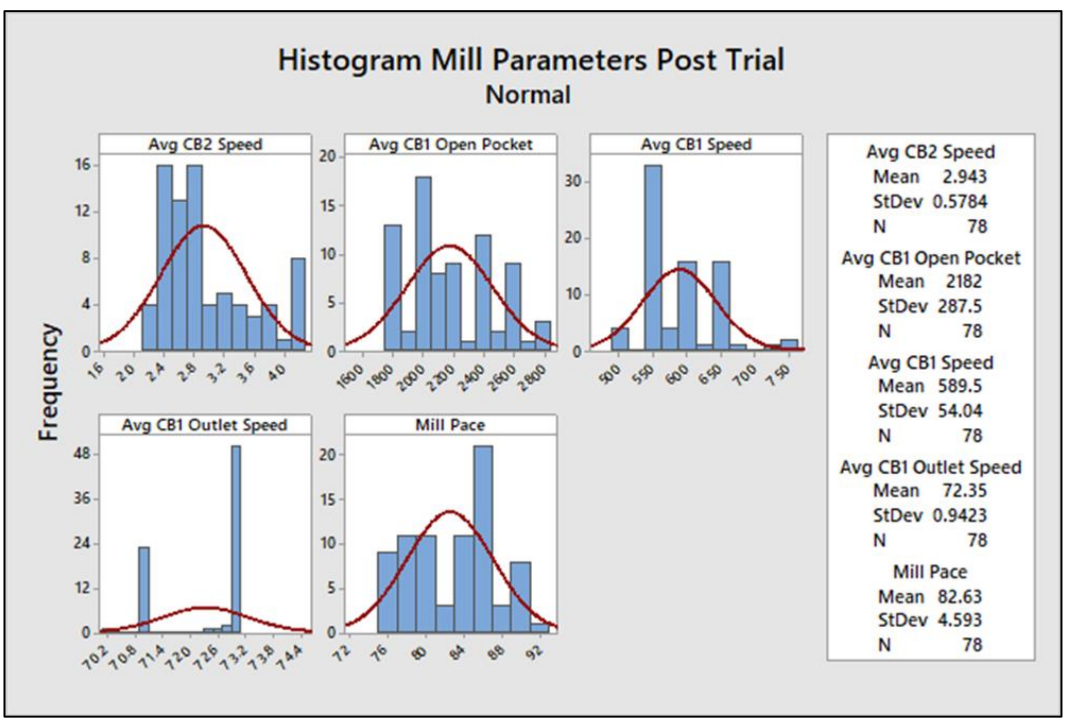


Figure 4-21: Histogram of mill parameters post cooling trial

4.7 Control: Blocking Actions

The team adopted the best practices learned from the cooling trial and updated operating procedures to ensure the result did not back slide. The new operating standards included set points for each process step and for each material grade. Over the next 12 cycles the team utilized this method to run high alloy products. With this method the team was able to achieve positive results and reduce the number of bowed pipe defects and the delay time associated to handling them. Figures 4-22, 4-23 and 4-24, 4-25 show the results achieved by the CIT.

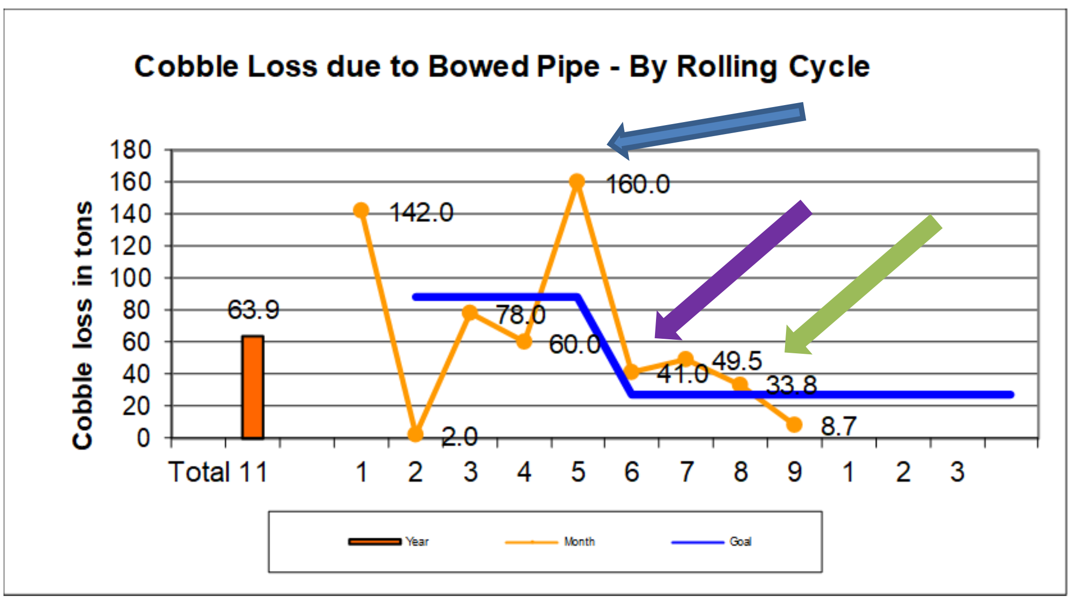


Figure 4-22: Primary Indicator data by cycle (2011)

Note: The first arrow (blue) is the start of the project, the second arrow (purple) are when the first trials started. The third (green) arrow represents when new practices were implemented

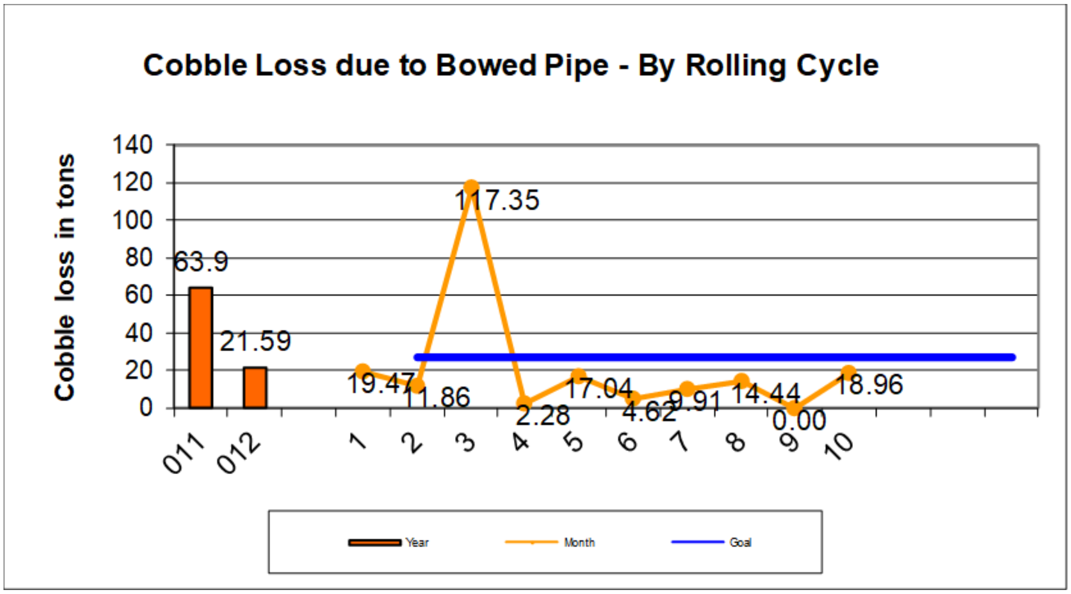


Figure 4-23: Primary Indicator data continuation (2012)

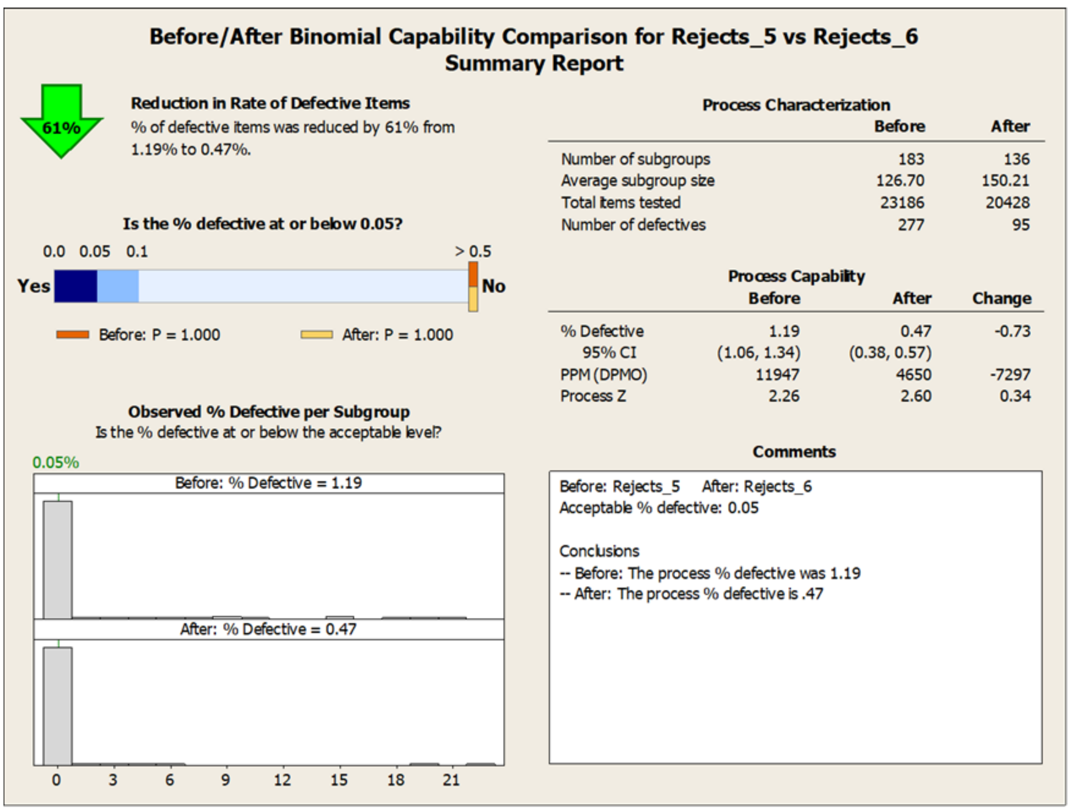


Figure 4-24: % Defective comparison before CIT and after CIT

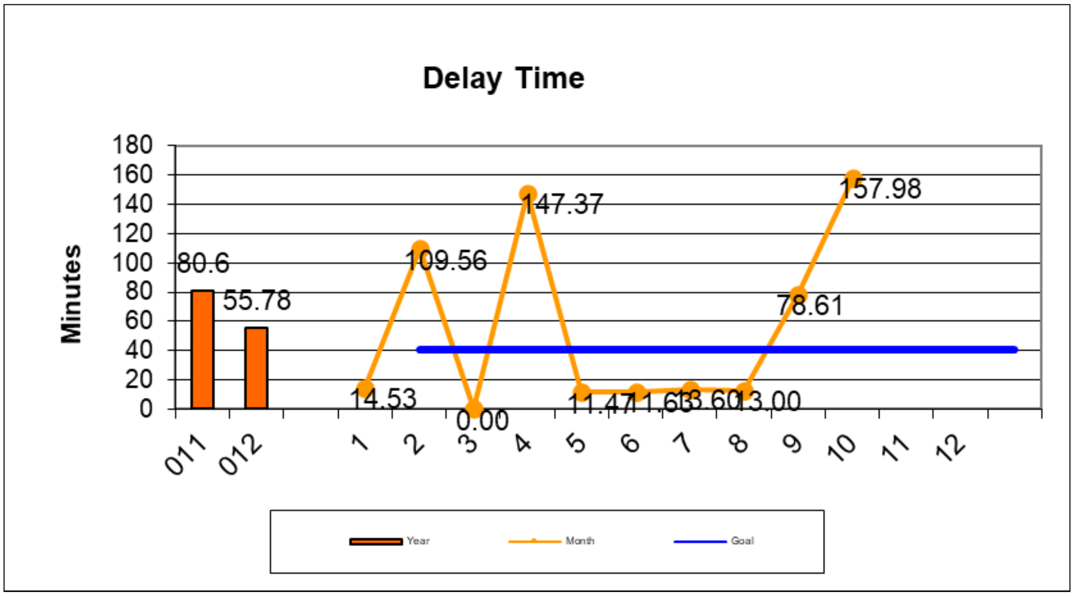


Figure 4-25: Secondary indicator data for mill delay time associated with bowed pipe rejects

The team was able to meet or over achieve the rejects goal eleven out of fourteen months. Taking the average of bowed pipe defects from 88 tons per cycle down to 27 tons per cycle (70% reduction) which met the goal established by the team and steering committee. The reject percentage decreased from 1.19% down to .47% which represents a reduction of 61%. The team was also able to reduce delay time associated to bowed pipe defects from 80.6 minutes per cycle down to 55.8 minutes per cycle which represents a reduction of 31%. With this effort the team was able to save a total of $420,843 in material costs and man hours and add an additional 5% to the mill's capacity over two years. The added capacity gave Vallourec Star the ability to sell more products over this time span. Resulting in an additional $3.5 million dollars in revenue.

Chapter 5 CONCLUSIONS

Six Sigma was investigated and piloted inside of the oil and gas industry more specifically inside of the seamless tube mill inside of Vallourec Star. This research answered the questions: Firstly, Could the Six Sigma methodology be used to identify the causes of bowed pipe rejects? Secondly, could Six Sigma significantly reduce these defects? This research has proven that Six Sigma is an effective approach at solving quality problems inside of the oil and gas industry. This research supports that adapting the approach and tools gives a higher chance of success and sustainability.

The methodology was tailored to match the needs and level of improvement maturity inside of Vallourec Star. The Six Sigma approach was piloted on a high visibility project inside of the seamless rolling mill. Key pieces of the methodology were packaged into a program which included a training plan for each level of the organization, a Critical to Quality (CTQ) matrix for selecting projects, a project roadmap for navigating DMAIC and special steering committee reviews specifically for Six Sigma projects. This approach proved successful for Vallourec Star. As a result, Vallourec Star has launched and completed 11 Six Sigma projects between their three facilities between 2011 – 2014. Vallourec Star has also trained 9 Six Sigma black belts, 1 Master black belt and 5 green belts. Six Sigma has added another dimension to the improvement program and as a result between 2011 and 2014 Vallourec Star has realized approximately $8 million dollars in cost savings from their CIT projects.

Implementation of the Six Sigma methodology inside of Vallourec Star has proven that it can be viable in any industry. The oil and gas industry could benefit significantly by investing its time, talent and intellectual capital in deploying Six Sigma.

Works Cited

[1] W. Sölken, ""Explore the World of Piping." Steel Pipe Manufacturing Processes," 2008.

[2] S. T. R.S. Buell, "Application of Lean Six Sigma in Oilfield Operations," ChevronTexaco, No Date.

[3] Vallourec, September 2019. [Online]. Available: https://www.vallourec.com/.

[4] M. J. H. a. R. Schroeder, Six Sigma: The Breakthrough Management Strategy Revolutionizing the World's Top Corporations., New York: Currency, 2000.

[5] M. J. H. a. J. R. Lawson, Six Sigma Producibility Analysis and Process Characterization, MA: Addison-Wesley, 1992.

[6] M. J. H. a. D. R. Linsenmann, The Six Sigma Fieldbook: How Dupont Successfully Implemented the Six Sigma Breakthrough Management Strategy., New York: Currency/Doubleday, 2006.

[7] P. S. P. a. L. Holpp., What Is Six Sigma?, New York: McGraw-Hill, 2002.

[8] R. P. N. a. R. R. C. Peter S. Pande, The Six Sigma Way: How GE, Motorola, and Other Top Companies Are Honing Their Performance., New York: McGraw-Hill, 2000.

[9] R. P. N. a. R. R. C. Peter S. Pande, The Six Sigma Way Team Fieldbook: An Implementation Guide for Project Improvement Teams., New York: McGraw-Hill, 2002.

[10] P. Romanowski, Steel Pipe: A Guide for Design and Installation., N/A: American Waterworks Association,, 1989.

[11] Vallourec, ""Vallourec Star, LP." Vallourec Star, LP Is Leading Producer of OCTG in USA," 5 January 2013. [Online]. Available: www.vallourec.com.

[12] M. T. LLC, "Crude oil prices - 70 year historical chart," 10 May 2020. [Online]. Available: macrotrends.net.

[13] C. Helman, "The 15 Biggest Oil Bankruptcies (So Far).," *Forbes Magazine,* p. N/A, 2016.

[14] P. W. H. Cooper, "“Oil and Gas.” Strategy& - the Global Strategy Consulting Team at PwC,," 2019. [Online]. Available: https://www.strategyand.pwc.com/gx/en/industries/oil-gas.html.

[15] W. Solken, "Steel Pipe and Manufacturing Processes," 2008 - 2020. [Online]. Available: www.wermac.org/pipes/pipemaking.html..

[16] P. Buzas, *“Pipe Making 101.” Vallourec Star Manufacturing Processes.,* Youngstown, Ohio: Vallourec Star., 2011.

[17] R. B. a. A. K. Jiju Antony, World Class Applications of Six Sigma: Real world examples of success, London and New York: Routledge, 2006.

[18] a. B. S. S. Dr. Karl Heinz Brensing, "Steel Tube and Pipe Manufacturing Processes.," *Steel Tube and Pipe Manufacturing Processes,* p. 1–63, 2000, .

[19] S. F. Ellis, *“The Application Of Lean Six Sigma To Improve A Business Process: A Study Of The Order Processing Process At An Automobile Manufacturing Facility.,* South Carolina: University of South Carolina, 2016, 2016.

[20] C. Howell, "“Lean Inventory Optimization and Repair Strategy of Mandrel Bars at V&M Star.” IIE,," in *Industrial Engineering Research Conference*, Reno , 2011.

[21] J. Atanas, "Lean Six Sigma Applications in Oil and Gas Industry," *Case Studies.” International Journal of Scientific and Research Publications,,* p. 540–544, 2016.

[22] J. P. Wardt, "LEAN DRILLING - INTRODUCING THE APPLICATION OF AUTOMOTIVE LEAN MANUFACTURING TECHNIQUES TO WELL CONSTRUCTION," in *SPE Drilling Conference*, Dallas, 1994.

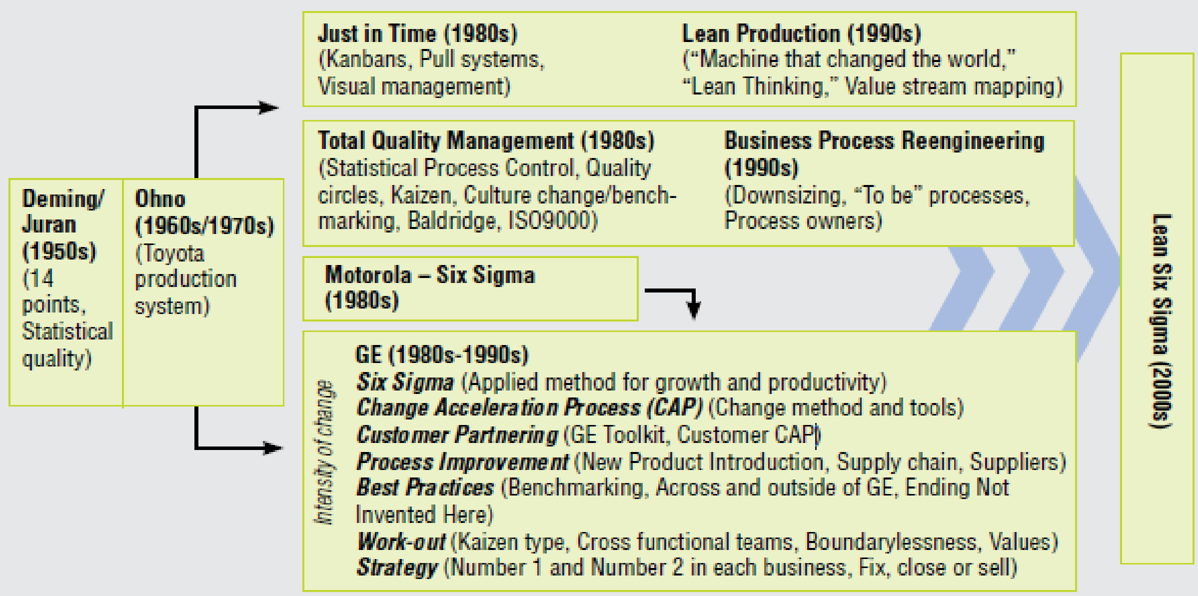
[23] S. S. Bob Skillman, *"Lean Six Sigma 103." Lean Six Sigma Black Belt Training.,* Kent, Ohio: Kent State University, Kent., 2011.

Chapter 6 Appendix A

Year of Inception of Six Sigma at Pioneering Companies	
Company Name	Year of Six Sigma Inception
Motorola	1986
Allied Signal (merged with Honeywell in 1999)	1994
GE	1995
Honeywell	1998
Ford	2000
Dow Chemical	1999

Table 6-1: Year of inception for Pioneering Companies

FIGURE 2.
Lean Six Sigma builds on the practical lessons learned from previous eras of operational improvement.



Source: IBM Global Business Services analysis.

Figure 6-1: Lean Six Sigma evolution

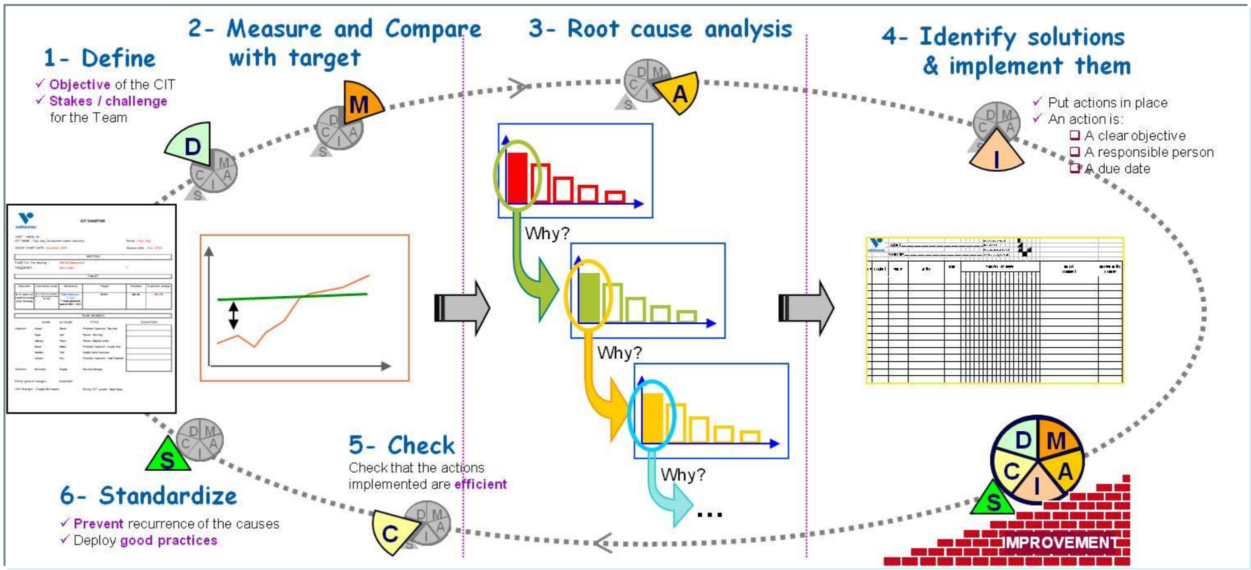


Figure 6-2: DMAIC visual roadmap